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Assessing ecosystem services and the alternatives of their future development in UNESCO Biosphere Reserves

Hodnocení ekosystémových služeb a alternativ jejich dalšího vývoje v biosférických rezervacích UNESCO

Doctoral thesis

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Annotation

The provision of ecosystem services within social-ecological systems is influenced by multiple environmental and anthropogenic driving forces, affecting natural ecosystems. At the same time, the capacity of ecosystems to concurrently provide different types of ecosystem services is inherently limited. Thus, ecosystem changes and their effect on ecosystem services have direct implications for human existence and well-being.

The aim of this thesis is to present a modelling approach to assess regulating, provisioning and cultural ecosystem services and to quantify their potential trade-offs, illustrated by two case studies carried out in selected UNESCO Biosphere Reserves in the Czech Republic, Třeboň Basin Biosphere Reserve and Šumava Biosphere Reserve. Both of the selected case study areas are characterized by high levels of natural and cultural assets and challenges regarding future landscape management.

In this study, first the social-ecological dynamics within the study areas was analysed by creating participative scenarios through collaboration with local stakeholders, eliciting their preferences regarding future landscape development to 2050. Second, the impact of the scenarios on ecosystem services and their trade-offs were assessed using a combination of spatially explicit models and modelling approaches.

The results indicate that while scenarios promoting economic revenues from landscapes caused substantial trade-offs among ecosystem services, conservational scenarios provided higher levels of ecosystem services with lower trade-offs. This study illustrates that while some stakeholder-created scenarios favoured managing ecosystems for short-term economic revenues, incorporating the provision of ecosystem services and their trade-offs shows that environmentally focused scenarios provide higher long-term benefits.

The conclusions of this study emphasize the importance of assessing ecosystem services trade-offs for sustainable landscape management and well-informed spatial planning and decision-making. At the same time, this study aims to contribute to the development of long-term socio-ecological research (LTSER) in the Czech Republic.

Anotace

Poskytování ekosystémových služeb v rámci sociálně-ekologických systémů je ovlivňováno řadou environmentálních a antropogenních hnacích sil, ovlivňujících přírodní ekosystémy. Kapacita ekosystémů současně poskytovat různé typy ekosystémových služeb je zároveň z podstaty limitována. Změny ekosystémů a související produkce ekosystémových služeb proto mají přímé důsledky pro existenci člověka a jeho blahobyt.

Cílem předkládané práce je představit modelovací přístup hodnotící regulační, zásobovací a kulturní ekosystémové služby a kvantifikující jejich potenciální rozpory (trade-offs). Tento přístup je ilustrován dvěma případovými studiemi, uskutečněnými ve vybraných biosférických rezervacích UNESCO v České republice – Biosférické rezervaci Třeboňsko a Biosférické rezervaci Šumava. Obě tyto oblasti jsou charakterizovány vysokými úrovněmi přírodního a kulturního bohatství, a zároveň jsou typické neshodami při definování priorit budoucího vývoje krajiny a krajinného managementu.

Prvním krokem této práce byla analýza sociálně-ekologické dynamiky studovaných oblastí pomocí série participativních scénářů ve spolupráci s místními zúčastněnými stranami. V této části práce byly zjištěny preference zúčastněných stran ohledně vývoje krajiny studovaných oblastí do roku 2050. Následně byly zhodnoceny dopady jednotlivých scénářů na ekosystémové služby a jejich rozpory s využitím kombinace prostorově explicitních modelů a modelovacích přístupů.

Výsledky práce ukazují, že zatímco scénáře upřednostňující ekonomické přínosy generované krajinou byly typické značnými rozpory mezi ekosystémovými službami, scénáře upřednostňující ochranu krajiny poskytovaly vyšší úrovně ekosystémových služeb s nižšími rozpory.

Závěry studie ukazují, že zatímco některé participativně vytvořené scénáře preferovaly spravování ekosystémů za účelem okamžitého ekonomického zhodnocení, započítání ekosystémových služeb a jejich rozporů ilustruje, že environmentálně zaměřené scénáře přinášejí vyšší dlouhodobé přínosy.

Závěry práce proto zdůrazňují význam hodnocení ekosystémových služeb a jejich rozporů pro udržitelný management krajiny, územní plánování a rozhodování o krajině. Účelem této disertační práce je též přispět k rozvoji dlouhodobého socio-ekologického výzkumu (long-term socio-ecological research, LTSER) v České republice.

Key words

Ecosystem services, trade-offs, scenarios, participatory approaches, stakeholders, land use and land cover change, modelling, InVEST, Třeboň Basin, Šumava, Czech Republic, long-term socio-ecological research (LTSER)

Klíčová slova

Ekosystémové služby, rozpory, scénáře, participativní přístupy, zúčastněné strany, změna krajinného pokryvu a využití území, modelování, InVEST, Třeboňsko, Šumava, Česká republika, dlouhodobý socio-ekologický výzkum (LTSER)

Declaration

Hereby I declare that I have written this doctoral thesis by myself, using solely the references and data cited and presented in the thesis. I declare that I have not been awarded other degree or diploma for this thesis or its substantial part. I give approval to make this thesis accessible by Charles University libraries and the electronic Thesis Repository of Charles University, to be utilized for study purposes in accordance with the copyrights.

Prague, 6 June 2016 Zuzana V. Harmáčková

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Table of Contents

List of Abbreviations

ALARM	Assessing Large-scale environmental Risks for biodiversity with tested Methods
ARIES	Artificial Intelligence for Ecosystem Services
BAMBU	Business As Might Be Usual
BaU	Business as Usual
BR	Biosphere Reserve
CAS	Czech Academy of Sciences
CICES	Common International Classification of Ecosystem Services
CLC	CORINE Land Cover
EEA	European Environment Agency
ESTIMAP	Ecosystem Service Mapping Tool
EU	European Union
GIS	Geographic Information Systems
GRAS	Growth Applied Strategy
InVEST	Integrated Valuation of Ecosystem Services and Trade-offs
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
LAI	Landscape Aesthetics Index
LTER	Long-term ecological research
LTSER	Long-term socio-ecological research
LULC	Land use and land cover
MA	Millenium Ecosystem Assessment
MAES	Mapping and Assessment of Ecosystems and their Services
NP	National Park
PLA	Protected Landscape Area
RCP	Representative Concentration Pathways
REACH	Registration, Evaluation, Authorization and Restriction of Chemical Substances
RPI	Recreation Potential Index
SEDG	Sustainable European Development Goal

SEEA	System of Environmental-Economic Accounting
SRES	Special Report on Emission Scenarios
TEEB	The Economics of Ecosystems and Biodiversity
UNESCO	United Nations Organization for Education, Science and Culture
UNFCCC	United Nations Framework Convention on Climate Change
UNSD	United Nations Statistical Division

List of Figures

List of Tables

1 Introduction

1.1 Ecosystem services

Ecosystem services (ES), defined as the contribution of natural ecosystems to human well-being, have been recognized as one of the most important preconditions of the existence and welfare of human society (MA, 2005; TEEB, 2010). Therefore, ES present a critical component of interaction between humans and nature and their provision has become a matter of concern for decision-makers on all governance levels (Daily et al., 2009) (Figure 1). ES assessments have gained considerable momentum in assisting decision-making on nature conservation and landscape management, as the concept of ES presents an opportunity to base landscape decisions on scientific findings and strengthen the science-policy link.

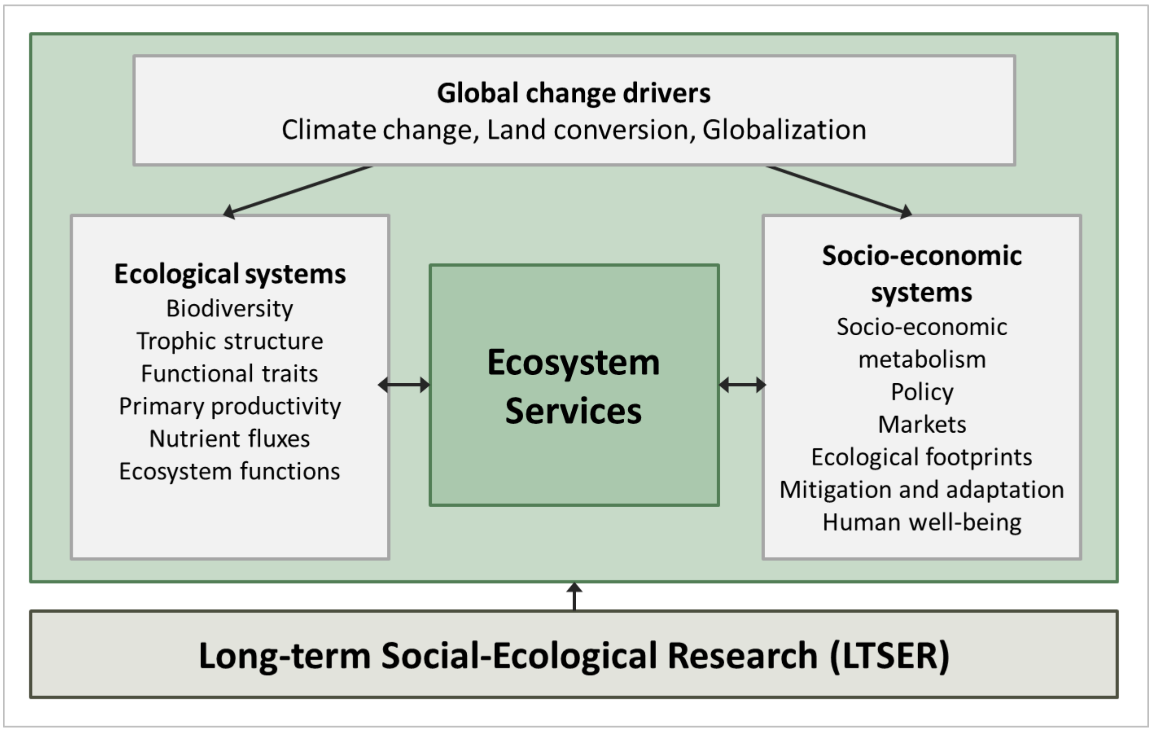


Figure 1. Conceptual framework of socio-ecological systems.
(Source: According to Haberl et al., 2006; Collins et al., 2011)

The provision of ES fundamentally depends on biodiversity, i.e. the existence and variability of ecosystems, species, their functional traits and genetic variety (CBD, 2010; EC, 2011). Although biodiversity is not commonly perceived as an ecosystem service *per se*, it presents a vital precondition for ecosystem functioning, as well as consequent provision of ES, on which human well-being directly depends (MA, 2005; Fischer et al., 2006; Rockström et al., 2009; Cardinale et al., 2012). Multiple studies have illustrated positive correlations between biodiversity levels and the provision of ES (MA, 2005; Egoh et al., 2009; Maes et al., 2012). Consequently, long-term social-ecological research (LTSER) endeavours aim to broaden the evidence basis to further demonstrate the importance of biodiversity conservation for sustainable provision of ES and human well-being (Lotze-Campen, 2008; Ohl et al., 2010). However, it is important to emphasize that at the same time, the position of biodiversity in the ES framework has been under continuous discussion (de Groot et al., 2010).

1.1.1 Ecosystem services within social-ecological systems

ES represent a critical component of interaction within social-ecological systems (SES) (Haberl et al., 2006; Collins et al., 2011), which are defined as complex adaptive systems consisting of interconnected socio-economic and ecological systems, characterized by complex dynamics and non-linear relationships with multiple feedback-loops and thresholds (Rammel et al., 2007). In such systems, ES present the link between natural ecosystems and human society (Figure 1) (Nassl and Löffler, 2015). The SES theory emphasizes mutual interrelations between anthropogenic and ecological drivers of ecosystem change (Bennett et al., 2003; Redman et al., 2004), and thus presents a theoretical concept widely operationalized in nature conservation and landscape protection (Miller et al., 2012). Consequently, the SES theory presents the basis of LTSER, which aims to establish platforms devoted to long-term monitoring and research of socio-economic and ecological driving forces and their impact on ecosystem change (Haberl et al., 2006; Ohl et al., 2010; Mauz et al., 2012).

1.1.2 Definitions of ecosystem services

In the last two decades of ES research, multiple definitions of ES have been introduced. The most commonly cited definitions of ES are for example:

- "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life" (Daily, 1997),
- "the benefits human populations derive, directly or indirectly, from ecosystem functions" (Costanza et al., 1997),
- "the benefits people obtain from ecosystems" (MA, 2005),

- “[the] components of nature, directly enjoyed, consumed, or used to yield human well-being” (Boyd and Banzhaf, 2007),

- “the aspects of ecosystems utilized (actively or passively) to produce human well-being” (Fisher et al., 2009).

This indicative list of definitions illustrates that ES present the contribution of natural ecosystems to the benefits consumed by humans, generating human well-being. However, one generally accepted definition remains to be specified.

Notably, there has been a persistent ambiguity in the literature regarding the difference between *ecosystem services* and *ecosystem functions* (Wallace, 2007; Burkhard et al., 2012; Van Oudenhoven et al., 2012). A growing consensus is that ecosystem functions present the capacity of ecosystems to generate ecosystem goods and ES, which are in turn actually consumed by human society (de Groot et al., 2010). This conceptualization has been reinforced by the concept of *ecosystem service cascade*, highlighting the links between biophysical aspects of ecosystems, biodiversity and human well-being (Haines-Young and Potschin, 2010; Spangenberg et al., 2014). The ES cascade comprises a chain of *ecosystem structure and processes* (e.g. net primary productivity), *ecosystem functions* (e.g. biomass production), *ecosystem services* (e.g. harvestable agricultural production), *benefits* (e.g. fulfilment of nutrition needs) and *value or human well-being* (e.g. economic revenues from food sales, human health).

Another widely discussed aspect is the difference between *final* ES (such as recreational enjoyment of a landscape) and *intermediate* ES (such as use of water for irrigation of agricultural plants, later consumed by final users) (Boyd and Banzhaf, 2007; Fisher et al., 2009). Such a distinction is particularly important to avoid double counting in economic evaluation of ES (UN, 2014). Furthermore, the notion of ES as *flows* between ecosystems and economic units, contributing to human well-being, has been recently introduced, especially for the purposes of economic evaluation of ES (TEEB, 2010; UN, 2014).

Apparently, the definition of ES has undergone a continuous development and the conceptualization and hierarchy of ES remain under discussion in the scientific and practitioners’ communities (Villamagna et al., 2013).

1.2 Classifications of ecosystem services

The concept of ES has been intensively developed by scientific and practitioners' communities in the past two decades. As a result, multiple classifications of ES have been established, which are introduced in the following sections.

1.2.1 Millenium Ecosystem Assessment

The fundamental classification of ES was introduced by the Millenium Ecosystem Assessment, finalized in 2005 (MA, 2005), and further classifications largely draw from this initial endeavour to classify ES.

The MA recognizes supporting, regulating, provisioning and cultural ES. Supporting services are "those that are necessary for the production of all other ecosystem services", such as photosynthesis, soil formation and nutrient cycling. Provisioning services are the "products obtained from ecosystems", e.g. food, fibres, fuelwood, biochemicals, genetic materials and ornamental resources. Regulating services are the "benefits obtained from the regulation of ecosystem processes", meaning the services necessary to sustain a suitable and benign environment for human existence, such as climate regulation, water regulation and purification, pest regulation and pollination. Cultural services are multiple "nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences" (MA, 2005).

The details of the classification including links to human well-being are provided in Figure A1.

1.2.2 The Economics of Ecosystems and Biodiversity

The classification of ES by The Economics of Ecosystems and Biodiversity initiative resembles the previous one by MA (TEEB, 2010). Nevertheless, a slight development in ES class definitions occurred under the TEEB classification, adjusting them for the purpose of economic evaluation.

In TEEB, provisioning services are the "material outputs from ecosystems", including food, water and other resources. Regulating services are the "services that ecosystems provide by acting as regulators, e.g. regulating the quality of air and soil or by providing flood and disease control". Habitat or Supporting services "underpin almost all other services" by providing "living spaces for plants or animals" and maintaining "a diversity of different breeds of plants and animals". Cultural services include "the non-material benefits people obtain from contact with ecosystems”, including “aesthetic, spiritual and psychological benefits”.

The details of the TEEB classification, including further examples, are provided in Figure A2.

In subsequent classifications, supporting services have been generally omitted, being redefined as ecosystem structure, processes and functions, underpinning the provision of ecosystem services (de Groot et al., 2010).

1.2.3 The Common International Classification of Ecosystem Services (CICES)

The Common International Classification of Ecosystem Services (CICES), developed primarily for the use within the EU policies on behalf of the European Environment Agency (EEA), presents a framework aiming to bridge multiple existing classifications of ES. Furthermore, CICES has been gradually developed to comply with its potential future use within the System of Environmental-Economic Accounting (SEEA), which is currently being led by the United Nations Statistical Division (UNSD).

CICES does not aim to replace other existing classifications of ES, but to facilitate comparison among different classifications. At the same time, rather than an exhaustive framework, it is intended to develop over time in relation to its new applications (EEA, 2015).

As the above described classification schemes, CICES recognizes provisioning, regulating services, as well as cultural services, with the exception of supporting services, originally defined in the MA, which are treated as part of the underlying structures, process and functions of ecosystems within CICES (Haines-Young and Potschin, 2013).

Unlike the previous assessments, CICES introduces a multiple-level hierarchy of ES classification (EEA, 2015). Such a hierarchical structure is operational for ecosystem accounting within SEEA and addresses scale issues and geographical differences, as the broader hierarchical categories can be used at broader spatial scales, while more specific classes might be used at the local level (Figure 2).

The summary of the CICES 4.3 hierarchical classification of ES with selected examples is provided in Table A1. The link of the CICES classification to the MA and TEEB classifications is provided in Table A2.

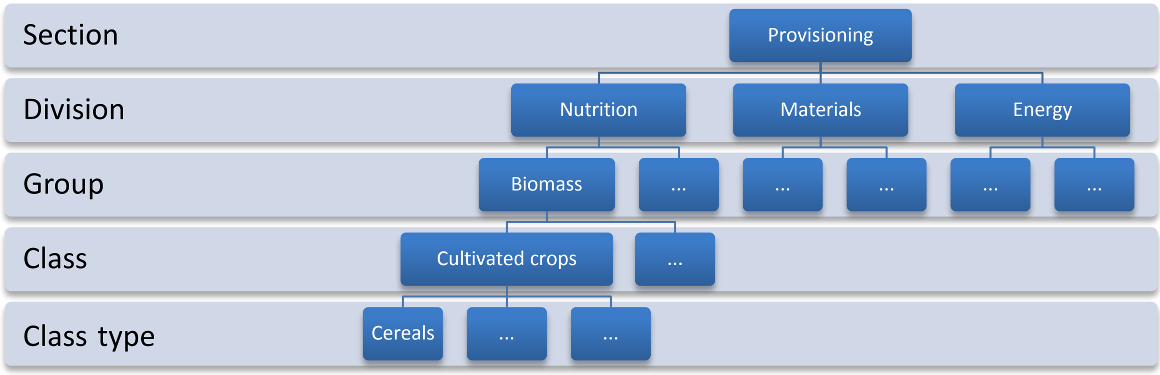


Figure 2. The hierarchy of the CICES classification.
(Source: According to EEA, 2015)

1.2.4 Other classifications

In addition to the above introduced classifications, multiple other endeavours to classify ES have been undertaken. For instance, classifications emphasizing the final consumption of ecosystem goods and services, as well as the direct link to beneficiaries, have been developed for economic-evaluation purposes (Boyd and Banzhaf, 2007; Fisher et al., 2009; Landers and Nahlik, 2013). Furthermore, alternative classifications based on aspects such as excludability and rivalness, spatial characteristics (Costanza, 2008), or human values (Wallace, 2007) have been developed. Other classifications have been established for the purposes of national ES assessments (UK NEA, 2011).

In general, the most commonly used classifications of ES recognize the classes of provisioning, regulating, and cultural services.

At the same time, consensus prevails that the scientific community is not supposed to reach a single ultimate classification of ES, but to develop multiple classifications to best serve diverse purposes of ES analyses (Costanza, 2008).

1.3 Related concepts

Multiple related concepts have been developed to take into account additional aspects of human-nature interactions not covered by the concept of *ecosystem services*. First, the concept of *ecosystem disservices* has emerged to capture the fact that ecosystems do not influence humans and society solely in positive ways by contributing to the benefits people obtain from nature (Lyytimäki, 2014; Von Döhren and Haase, 2015). On the contrary, ecosystem disservices cover the aspects of ecosystem functioning that influence humans and society negatively, such as by providing the conditions for the spread of pests and diseases. While many types of ecosystem disservices are linked to agriculture (Zhang et al., 2007), recent studies have also focused on the disservices originating from urban ecosystems (Gómez-Baggethun and Barton, 2013). At the same time, the notion of negative phenomena linked to ES has been described even before the introduction of the concept of ecosystem disservices (Bolund and Hunhammar, 1999).

The second concept related to and expanding ES are *landscape services*. In general, this concept largely overlaps with ES, with some studies using these terms interchangeably (de Groot et al., 2010). However, from a slightly different perspective, landscape services can be perceived as a more holistic approach, acknowledging not only the role of individual ecosystems, but also the role of mutual links and relationships between ecosystems, as well as their spatial configuration in multifunctional landscapes, in the provision of services benefiting human society (Termorshuizen and Opdam, 2009). As such, landscape services emphasize the interlinked social-ecological aspect of landscape functioning and thus have a distinct sustainability dimension. Unlike ES, the concept of landscape services emphasizes their place-based nature, which is contrary to a traditional economic evaluation of ES (not necessarily linked to a specific spatial configuration of a certain landscape) (Termorshuizen and Opdam, 2009; Fagerholm et al., 2012).

In this thesis, solely the concept of ES is applied, for two reasons. First, out of the three introduced concepts, it has been most widely established in the literature. Second, it matches the aim of the thesis to biophysically assess potential future contribution of ecosystems to human well-being in selected case study areas.

1.4 Assessment approaches

This section summarizes the approaches utilized to assess the provision of ES. First, it reviews approaches applicable in the assessment of different classes of ES (as introduced in the previous section, e.g. provisioning, regulating and cultural). Subsequently, the section provides an overview of available multi-service modelling tools.

In general, approaches to economic evaluation were outside the scope of this study. Therefore, the following sections generally prioritize an overview of biophysical assessments of ES which relate to the aim of this thesis. Nevertheless, in the case of provisioning services, we highlight several studies applying economic-evaluation approaches, since economic evaluation is the most widely used type of assessment of provisioning services.

1.4.1 Provisioning services

Economic assessments of provisioning services generally benefit from the availability of market-based and statistical data. Although widely used, the disadvantage of economic assessments is that they do not allow for comparison with those types of ES that are difficult to assess in monetary terms (e.g. landscape aesthetics). On the other hand, such comparison is facilitated by applying biophysical approaches to assess provisioning ES, illustrated by several examples below.

1.4.1.1 Economic assessments

A rather complex approach to economic assessment of provisioning ES was used by Polasky et al. (2008), who developed an array of economic models to predict the net present value of marketed goods and services derived from selected landscapes. In their study, specific models were used to assess the net present values of economic returns (1) from agricultural land-use and (2) from managed forestry, taking into account:

- Annual yields (as a function of soil capability class, irrigation potential and parcel spatial position in the case of agricultural products),
- Production or logging costs,
- Observed market prices of crops and timber.

This model was applied on an array of theoretical landscape compositions and land use patterns, taking into account future time-span by using the concept of net present value and discounting. Nevertheless, the models assume constant market prices for all theoretical landscapes, which collides with a scenario approach, assuming different socio-economic development and conditions for various potential futures.

To quantify timber production in economic terms, Grêt-Regamey et al. (2008) used the extent of forested area as a proxy indicator, taking into account the approximate proportion of forest growth removed annually and the proportion of canopy cover in different forest patches, followed by economic assessment based on market-price estimates. Similarly, the indicators of produced quantities of food, cultivated hectares and food market prices were used to assess food provision in a study by Busch et al. (2012), while tonnes of standing timber and timber market prices were used as the indicators of timber provision.

Goldstein et al. (2012) quantified provisioning ES in the form of the net present value of agricultural land, accounting for projected real property taxes, agricultural land rental rates and real estate prices for bulk sale of agricultural lands. In their regional-scale analysis, Ruijs et al. (2013) calculated agricultural revenues as an input into an ES trade-off analysis, using data on land use, cropping pattern together with statistical data on yields and prices per crop type.

1.4.1.2 Biophysical assessments

Biophysical approaches reduce the complexity of modelling future development of ES provision, as they focus solely on the biophysical potential of the landscape to provide goods and services and disregard economic parameters such as potential future development of market prices and the trade with agricultural and forest products.

Among the biophysical assessments of provisioning ES, two major approaches can be distinguished: projecting the yields of agricultural and forest products, and estimating solely the extent of agricultural and forest areas as a proxy for the capacity of a landscape to provide these goods and services. Both approaches are characterized by different types of uncertainties. While using agricultural yields and timber provision allows for a more detailed estimate of the actual ES provision, projecting potential future changes in agricultural and forestry yields is burdened by high uncertainties. On the other hand, although focusing solely on the extent of the agricultural and forest area provides a coarse estimate of the actual provision of agricultural goods and services, it generates coherent estimates of the current and the future state without additional source of uncertainty in the form of the projections of future yields.

Among the biophysical assessments of provisioning ES, a relatively feasible way to assess provisioning ES was applied by Raudsepp-Hearne et al. (2010), who utilized proxy data, namely the percentage of cropland in selected municipalities, and the number of cattle per kilometre square. Using data from national censuses and data provided by municipality authorities, the authors argue that this approach, based on high-quality and easily accessible data, ensures an acceptable trade-off between accuracy and feasibility. A similar approach to the assessment of provisioning ES was applied by Queiroz et al. (2015), who assessed provisioning services based on the extent of cultivated area and number of cattle owned by agricultural holdings per kilometre square. Commercial forest area was used as a proxy for timber and forest product provision.

Within the EU MAES initiative (Mapping and Assessment of Ecosystems and their Services), the suggested indicators used in pilot maps of ES provision comprise the annual harvested production of food crops, the number of grazing livestock, timber growing stock and total timber removal (Maes et al., 2015). Additional indicators suggested within MAES to assess provisioning services include food crop area, forest biomass stock, forest biomass increment, forest timber production, forest tree volume and harvesting rates.

Similarly, Burkhard et al. (2012) suggest number of plants per hectare (animals per hectare, respectively) or energy in kJ per hectare as an indicator of crop provision (livestock, respectively). For timber provision, the authors suggest the amount of wood per hectare, tree biomass per hectare or energy in kJ per hectare. Lautenbach et al. (2011) use the indicator of arable land area belonging to the highest soil fertility classes as a proxy for food production.

In the Czech Republic, Lorencová et al. (2013) focused directly on wheat, barley and maize yields based on statistical data provided by Czech Statistical Office in their study on temporal development of ES provided by agricultural land.

According to Queiroz et al. (2015), while an increasing number of assessments of multiple ES have emerged in the past two decades, the vast majority of these studies apply different methodology, which hampers cross-study comparison. At the same time, comparison between studies contributes to ES research, as it allows generalizing local and regional findings, and helps to distinguish the effect of context-dependent driving forces from real interactions between services. Therefore, comparability to other ES studies has been acknowledged as a highly productive aspect of ES studies, which was respected in the methodology of the present study.

1.4.2 Regulating services

Regulating services, such as climate regulation, water regulation and sediment retention, have been recognized as particularly vulnerable to ecosystem conversion and degradation (Zedler and Kercher, 2005). The level of regulating ES also tends to decrease with accented production of provisioning ES (Hansson et al., 2005; Bennett et al., 2009; Raudsepp-Hearne et al., 2010). At the same time, regulating ES serve as the basis for other types of ES, especially provisioning. Evidently, human activities influence the provision of regulating ES, which may in turn affect other ES with implications for human welfare and well-being (MA, 2005; TEEB, 2010).

Biophysical assessments of regulating services in the literature range from expert-based approaches to process-based modelling, nested in geology, hydrology, pedology and ecology.

Among the expert-based indicative approaches, several studies by Burkhard et al. (Burkhard et al., 2009, 2012; Jacobs et al., 2014) introduce a two dimensional matrix, assigning each type of a land cover a relative score of ES provision based on expert opinion. Provided that a consensus among experts is reached regarding what level of regulating ES is provided by which type of land cover, and the land cover classification is sufficiently detailed, the matrix approach is beneficial in the cases that it is not possible to conduct model-based assessment.

On the other hand, especially water-related regulating ES can be modelled using elaborate process-based models originally developed for hydrological purposes, such as SWAT (Soil and Water Assessment Tool, http://swat.tamu.edu/) or VIC (Variable Infiltration Capacity Macroscale Hydrologic Model, http://vic.readthedocs.org). These models facilitate accurate modelling of hydrological phenomena and related processes, such as nutrient leaching and water soil erosion, which can be, after adjustments, used as the basis for ES assessments. Nevertheless, these models are highly demanding in terms of data inputs and require collaboration with experienced hydrologists, which limit their use in ES assessment (Vigerstol and Aukema, 2011). For instance, among studies assessing regulating ES with specialized hydrological models, Nedkov et al. (Lautenbach et al., 2012; Nedkov and Burkhard, 2012) modelled water yields, water flow and potential flood levels in order to quantify the ability of ecosystems to retain flood-water, pollutants and sediments. Subsequently, they linked this information with societal demand for flood regulation and water purification.

Other tools focusing on the assessment of regulating ES are generally of constricted applicability in research. First, these tools are often proprietary (the license needs to be purchased) or require a commercially developed software, such as the MIMES model (Multi-scale Integrated Models of Ecosystem Services, http://www.afordablefutures.com/home) or the WEAP model (Water Evaluation And Planning, http://www.weap21.org/) (Boumans et al., 2015; Bhave et al., 2016), both focusing on the assessment of water-related processes and their dependency on changing environmental conditions.

Second, available web-based modelling tools are of a narrower scope, with a limited possibility of parametrization. For instance, the WaSSI tool (Water Supply Stress Index Model, http://www.wassiweb.sgcp.ncsu.edu/) is a web-based tool to model the effects of land use and land cover change, climate change, and water withdrawals on river flows, water supply stress, and carbon sequestration dynamics; however, limited to selected locations in North America and Africa (Caldwell et al., 2012).

In addition to the above introduced approaches, regulating services have also been assessed with tools parallelly modelling multiple types of ES (Nelson et al., 2009; Bagstad et al., 2012; Goldstein et al., 2012; Arkema et al., 2013; Balbi et al., 2015), which are listed in a separate section below.

1.4.3 Cultural services

Compared to the provisioning and regulating services, cultural ES present a subgroup of ES challenging in terms of definition and classification, and consequently, in terms of assessment (Daniel et al., 2012). Therefore, the following section aims to summarize current approaches to the conceptualization of cultural ES, in order to structure the following review of approaches to assess cultural ES.

Various definitions and classifications of cultural services have been developed, mainly within international and global synthetizing reports, as well as research articles on ES. Among global assessments, (MA, 2005) defines cultural ES as “the non-material benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation and aesthetic experiences". MA divides cultural services into several sub-classes, namely:

1. Cultural diversity, defined as the influence of ecosystem diversity on the diversity of cultures,
2. Spiritual and religious values, mediating the attachment of some religions and beliefs to ecosystems and their components, as well as spiritual fulfilment,
3. Knowledge systems, encompassing the influence of ecosystems on the types of knowledge systems developed by different cultures (e.g. traditional and formal),
4. Educational values, since ecosystems provide the basis for formal and informal education,
5. Inspiration, provided by ecosystems for art, folklore, national symbols, architecture, advertising, etc.,
6. Aesthetic values, comprising the visual qualities or aesthetic value of various aspects of ecosystems perceived and enjoyed by people, such as scenery and scenic beauty,
7. Social relations, which are influenced by ecosystems the cultures are hosted by (e.g. the relations within fishing societies differ in the type of social relations from nomadic herding to agricultural societies, based on the type of fisheries used),
8. Sense of place, associated with recognized features of ecosystems, which form people's environment,
9. Cultural heritage values, placed by many societies on historically important landscapes (so called "cultural landscapes") or culturally significant species.
10. Recreation and ecotourism supported by the characteristics of the natural of cultivated landscapes in particular areas.

The TEEB report (TEEB, 2010) defines cultural ES as "the non-material benefits people obtain from contact with ecosystems, including aesthetic, spiritual and psychological benefits". TEEB introduces a similar classification as MA, dividing cultural services into:

1. Contribution to recreation and mental and physical health,
2. Tourism,
3. Aesthetic appreciation and inspiration for culture, art and design,
4. Spiritual experience and sense of place,
5. Contribution to education.

On the European level, the CICES classification, attempting to bridge the MA and TEEB classifications, define cultural services as “the non-material, and normally non-consumptive, outputs of ecosystems that affect physical and mental states of people” (Haines-Young and Potschin, 2013). Nevertheless, the current report on CICES (Haines-Young and Potschin, 2013) emphasises that the area of cultural ES is particular problematic in terms of terminology, since in the case of cultural services, it is difficult to make a distinction between services and benefits (e.g. for recreation).

CICES recommends that “cultural services are primarily regarded as the physical settings, locations or situations that give rise to changes in the physical or mental states of people, and the character of which is fundamentally dependent on living processes; they can involve individual species, habitats and whole ecosystems. The settings can be semi-natural as well as natural settings (i.e. can include cultural landscapes) providing they are dependent on in situ living processes” (Haines-Young and Potschin, 2013). CICES further recognizes the distinction between settings supporting interactions that are used for physical activities such as hiking and angling, and intellectual or mental interactions involving analytical, symbolic and representational activities. Spiritual and religious settings are also recognised. The classification also covers the ‘existence’ and ‘bequest’ constructs that may arise from people’s beliefs or understandings.

Thus, on the level of classes, CICES distinguishes the following types of cultural services:

1. Experiential use of plants, animals and landscapes,
2. Physical use of landscapes,
3. Scientific interactions,
4. Educational interactions,

5. Heritage, cultural interactions,
6. Entertainment interactions,
7. Aesthetic interactions,
8. Symbolic interactions,
9. Sacred and/or religious interactions,
10. Existence values,
11. Bequest values.

In addition to the above listed types of cultural services, Burkhard et al. (2012) introduce the intrinsic value of biodiversity, defined as “the value of nature and species themselves, beyond economic or human benefits”. However, such a definition of an ecosystem service, not relating its value to direct or indirect benefits to people, is rather contested, and the intrinsic value of biodiversity is usually not considered as a cultural ES.

Costanza (2008) introduces a different perspective and classifies cultural ES as either global and not depending on spatial proximity, such as cultural or existence values of ecosystems, or dependent on users’ movement, e.g. dependent on the flow of people to unique natural features, such as in the case of recreation and valuing cultural and aesthetic features of ecosystems.

Wallace (2007) proposes to distinguish different types of cultural services based on the final benefit these services bring to human societies. While the final benefit proposed by the authors is socio-cultural fulfilment, the individual cultural services are classified based on the access to:

1. Spiritual/philosophical contentment,
2. A benign social group, including access to mates and being loved,
3. Recreation/leisure,
4. Meaningful occupation,
5. Aesthetics,

6. Opportunity values, capacity for cultural and biological evolution,

7. Knowledge/education resources,

8. Genetic resources.

Nevertheless, the authors describe their list of cultural services as indicative, requiring further development, especially in reference to different cultural systems and alternative value views (Costanza, 2008).

In a study by de Groot et al. (2002) introducing a classification of ES based on their underlying ecosystem functions, the authors define the intangible services of ecosystems as related to information functions. An indicative list of these underlying functions and their resulting goods and services is provided in Table 1.

Table 1. Information functions and related goods and services of natural and semi-natural ecosystems (according to de Groot et al., 2002).

Information functions	Goods and services (examples)
Aesthetic information	Enjoyment of scenery (scenic roads, housing, etc.)
Recreation	Travel to natural ecosystems for ecotourism, outdoor sports, etc.
Cultural and artistic information	Use of nature as motive in books, film, painting, folklore, national symbols, architect., advertising, etc.
Spiritual and historic information	Use of nature for religious or historic purposes (i.e. heritage value of natural ecosystems and features (such as old trees).
Science and education	Use of natural systems for school excursions, etc. Use of nature for scientific research.

In relation to economic evaluation of ES, Boyd and Banzhaf (2007) focus on examples of cultural services such as hiking, swimming, birding and angling, emphasizing the importance of proper definition and classification of ES to facilitate their assessment and evaluation.

In sum, multiple classifications and definitions of different types of cultural ES have been developed, focusing on multiple perspectives and aspects. While some types of cultural services can be modelled and captured in biophysical or economic terms, such as the consumption of recreational and touristic opportunities, assessed based on the numbers of visitors, for other cultural services, proxy data need to be utilized to estimate the capacity of ecosystem to provide a certain cultural service, e.g. in the case of the aesthetic aspects of landscapes. In some cases, such as the spiritual experience of ecosystems, the possibility of assessing the amount of the service provided remains questionable.

A distinctive characteristic of cultural ES is that most cultural services are directly experienced and intuitively appreciated, in contrast with e.g. regulating services, which are rarely recognized by stakeholders and the public (Daniel et al., 2012). As such, cultural ES have the potential to raise public support for nature conservation and environmental protection (Gobster et al., 2007). Nevertheless, cultural services are often characterized as intangible or subjective (see above), and thus difficult to quantify in biophysical or monetary terms. Therefore, their integration into the ES framework seems difficult. Another contested aspect of cultural services is their dependency on social constructs. Nevertheless, as recent studies show, a significant direct and indirect contribution from ecological structures and processes to cultural benefits can be attributed to ecosystems as their cultural services and numerous approaches are available to quantitatively or qualitatively assess this contribution (Daniel et al., 2012).

The diversity of cultural ES evident from the analysis above is in line with the wealth of approaches to their assessment (Kelemen et al., 2014). As stated above, in this section, we focus solely on assessment and modelling approaches based on spatial data and the physical basis of cultural ES, as well as their relation to physical landscape attributes and patterns, with various level of participatory input.

A significant part of studies assessing the provision and spatial distribution of cultural ES utilizes public participation GIS (PPGIS) approaches, using various mapping approaches to allow the public and stakeholders to express their opinion on the type and level of services provided by different types of landscapes. PPGIS has been utilized in numerous applications including nature conservation, landscape management and urban planning, as well as the assessments of landscape values related to cultural ES (Brown and Kyttä, 2014). Since participative collaboration with the general public and related mapping of social values for ES is beyond the scope of this study, further details on PPGIS approaches in the assessment of cultural ES can be found in (Raymond et al., 2009; Sherrouse et al., 2011; Brown and Fagerholm, 2015).

Another broad group of studies assess cultural ES from the perspective of landscape aesthetics, the physical characteristics of landscapes and visual landscape patterns. Apart from studies eliciting the perspectives of different cultural and stakeholder groups and perceptual surveys (Daniel, 2001), numerous studies focus on the biophysical basis of landscape aesthetics and the possibilities to assess it. These studies quantify the contributions of landforms, vegetative land cover and water features to aesthetic landscape quality, and use modelling and assessment mainly by GIS approaches. Although the conceptualizations of landscape aesthetics have been numerous and largely depend on the spatial setting of various studies, the vast majority of studies define landscape aesthetics through their visual characteristics, especially scenic beauty (Gobster et al., 2007).

GIS-based approaches to assess cultural ES naturally stem from perceptual studies, assessing stakeholder preferences regarding various landscape features. In this respect, a common reservation towards such a basis lies in the presumed differences in aesthetic preferences across individuals, demographic, ethnic or other groups (Hagerhall, 2001). However, existing perceptual assessments of landscapes have shown a substantial consensus, especially in the case of natural landscapes (Stamps, 1999). Thus, such studies linking landscape attributes to human perceptions can serve as a basis for further GIS-based assessments of landscape aesthetics.

Studies by Grêt-Regamey et al. (2007, 2008) present examples of elaborate GIS-based modelling approaches assessing scenic beauty of predominantly mountainous regions. The three-dimensional GIS model developed by the authors includes the effects of slope, aspect, distance, as well as the height of landscape features to calculate the proportion of different land cover areas making up the viewshed. Subsequently, the preferences of participants regarding landscapes are elicited through a photograph-based participative survey. This method also allows for digital altering of the survey photographs and thus eliciting the preferences regarding different landscape change scenarios.

There are numerous studies focusing on the general preferences of the public regarding various types of landscapes and landscape features, also examining the effect of various socio-economic aspects such as personal characteristics, residential location and environmental value orientations on landscape preferences. Multiple studies suggests that the strongest preferred landscapes are those with water related features as dominant attributes, followed by cultural landscapes (Howley, 2011; Völker and Kistemann, 2011). Further appreciated aspects of landscapes are diverse spatial patterns and spatial heterogeneity, as well as variety and complexity of landscape patterns (de la Fuente de Val et al., 2006). Tree cover and vegetation have different impacts on the perception of landscapes in the case of barren landscapes, where increasing proportion of tree cover is appreciated, and in vegetated landscapes, where additional increase in tree cover causes moderate or low increase in preferences (Jiang et al., 2015). Several studies emphasize the heterogeneity in landscape preferences according to participants' personal and socio-demographic characteristics (Swanwick, 2009). Therefore, the assumption that based on numerous previous perceptual surveys, a GIS-based estimate of landscape aesthetics is feasible, seems reasonable, provided the study area belongs to a landscape type and socio-economic context previously studied in perceptual surveys (Dramstad et al., 2006).

A purely GIS-based approach to the assessment of landscape aesthetics has been proposed and applied both on regional and European level (Otero Pastor et al., 2007; Martín Ramos and Otero Pastor, 2012). This approach is based on the theoretical assumption, drawn from previous landscape perception surveys, that in a given socio-cultural space, specific landscape parameters are valued as aesthetically pleasing, such as natural land cover types or mountainous terrain. Thus, spatial analysis is utilized to assign each part of a landscape a score based on the overlay of these parameters.

A similar GIS-based approach, denoted as ESTIMAP, has been developed to map the recreational potential of natural areas, based on their ecological quality and the proximity of desirable landscape features, such as water bodies (Paracchini et al., 2011, 2014; Maes et al., 2015). This approach facilitates a flexible combination of various landscape parameters, based on the locally-specific perception of their importance. For instance, terrain forms can be included in mountainous areas, where they are valued by tourists, while omitted in lowland regions, where other landscape features are sought. Furthermore, this approach has been applied within the EU-wide initiative on mapping ES (MAES).

As in the case of regulating services, cultural services can be modelled by several available tools for modelling multiple types of ES (Bagstad et al., 2014). This type of tools is summarized below.

1.4.4 Modelling tools for the assessment of multiple ecosystem services

Hitherto, multiple tools have been developed to facilitate the assessment of multiple ES. Since comprehensive reviews of such tools are available (Nemec and Raudsepp-Hearne, 2012; Bagstad, Semmens, Waage, et al., 2013), this section does not aim to provide an exhaustive list, but to highlight the most widely used modelling tools for multiple-ES assessment (Vigerstol and Aukema, 2011; Nemec and Raudsepp-Hearne, 2012; Bagstad, Semmens, and Winthrop, 2013).

InVEST (Integrated Valuation of Environmental Services and Trade-offs, http://www.naturalcapitalproject.org/invest/) has been developed by the Natural Capital Project initiative at Stanford University (Kareiva et al., 2011) as research and decision-support tool enabling spatially explicit assessment and evaluation of ES at various spatial scales. To date, the model has been applied in studies encompassing a wide range of geographic and climatic conditions and has been used for ES evaluation in various research projects worldwide, especially to compare different alternatives of potential future landscape development (Nelson et al., 2009; Tallis and Polasky, 2009; Isely et al., 2010; Goldstein et al., 2012).

InVEST presents a set of models using the approach of ecological production functions, which attributes different levels of ES provision to specific ecological and socio-economic characteristics of the study location (Kareiva et al. 2011). Individual modules of InVEST are based on different modelling principles, e.g. they operate as look-up tables (in the case of climate regulation), as well as partially process-based models (as in the case of water-related ES, such as hydropower production and water quality regulation).

The ARIES model (Artificial Intelligence for Ecosystem Services, http://aries.integratedmodelling.org/) presents a complex system for the integrated assessment of ES. Unlike InVEST, the ARIES model is designed to utilise probabilistic modelling based on Bayesian belief networks, which partly reduces potential error introduced by the use of incomplete or low-quality data (Villa et al., 2014).

The model is based on the conceptualization of ES as flows from the ecosystem of origin to human beneficiaries, which reflects the most current development in the conceptualization of ES (Villamagna et al., 2013; Villa et al., 2014). Thus, it enables modelling the original capacity of ecosystems to provide services, the potential and actual flow of ES, as well as the demand for ES by human society (together with multiple other aspects of these three phenomena).

For different ES, the ARIES tool utilizes separate modules, applied to model multiple terrestrial and water-related services. The tool has been utilized in several studies up to date (Bagstad et al., 2012, 2015; Balbi et al., 2015). The ARIES model is freely available; on the other hand, its application is hindered by substantial complexity and high requirements in terms of coding skills.

In other cases, multiple-service tools represent general guidelines or frameworks to organize the steps of ES assessment at a local level, such as TESSA (Toolkit for Ecosystem Service Site-based Assessment, http://tessa.tools/) (Peh et al., 2013).

1.5 Ecosystem-service trade-offs and synergies

Trade-offs among different types occur when "the provision of one ecosystem service is reduced as a consequence of increased use of another ecosystem service" (Rodriguez et al., 2006). Generally, ES trade-offs arise from the fact that in a limited time and space, ecosystems are only capable of providing a selected array of ES and not all ES can be maximized at the same time. Thus, trade-offs are inherently linked to human landscape management priorities and choices (Bennett and Balvanera, 2007). ES *synergies* represent a complementary concept, occurring in the cases when the provision of one ecosystem service parallelly enhances the provision of another one (Bennett et al., 2009).

Trade-offs are characterized by a spatial, temporal and reversibility dimension. While the spatial dimension refers to whether "the effects of the trade-off are felt locally or at a distant location", the temporal dimension is defined by whether "the effects take place relatively rapidly or slowly". Finally, the reversibility expresses the extent to which a hindered ES has the potential to return to its original state, once the disturbance ceases (Rodriguez et al., 2006).

Recent studies suggest that ES trade-offs occur mainly between provisioning services on the one hand, and cultural and regulating services on the other (Bennett et al., 2009; Nelson et al., 2009). For instance, intensive agricultural landscapes prioritizing food production are usually characterized by low provision of cultural and regulating services.

Nevertheless, particularly low capacity to provide regulating services (e.g. erosion control) may in turn negatively affect the provisioning potential of such areas. Thus, sensitive management strategies are needed to sustain balanced provision of multiple types of ES (Bennett et al., 2009).

ES trade-offs and synergies have been quantified using various numerical and statistical approaches, including:

- Calculation of exploratory statistics and subsequent comparison in relative terms, supplemented by comparison of spatial datasets (Nelson et al., 2009; Goldstein et al., 2012; Harmáčková and Vačkář, 2015),
- Application of correlation, principal component analysis and cluster analysis, supplemented by comparison of spatial datasets (Raudsepp-Hearne et al., 2010; Haase et al., 2012; Queiroz et al., 2015),
- Calculation of an indicator comparing relative change in the provision of ES compared to a unit change in one selected ES, e.g. climate regulation (Nelson et al., 2010).

A broad array of approaches to compare the provision of different ES and assess their trade-offs is related to economic evaluations, leading to comparisons in monetary terms, such as in the studies conducted within the TEEB initiative (TEEB, 2010) and others (Dymond et al., 2012). Nevertheless, approaches to economic evaluation were generally outside the scope of this study, which focused on a biophysical modelling framework.

1.6 Future provision of ecosystem services

1.6.1 Driving forces of ecosystem change

The provision of ES is conditioned by unimpaired state and functioning of ecosystems. However, current abrupt pace of ecosystem change on local, regional and global scales threatens to diminish the provision of ES and human well-being (MA, 2005; Rockström et al., 2009).

Global ecosystem change is induced by multiple indirect and direct drivers of both anthropogenic and environmental character. Furthermore, interactions among these drivers generate synergic or additive effects (MA, 2005). Thus, global ecosystem change is triggered by demographic, economic, technological and institutional driving forces, which in turn influence climate change, land transformation, pollution, biodiversity loss and other phenomena, affecting ecosystem extent and condition (Vitousek et al., 1997; MA, 2005).

First, climate change present a global-scale effect of these driving forces, influencing spatial distribution and resilience of ecosystems by changes in temperature and water regimes (IPCC, 2014). Second, habitat conversion, pollution, hunting and fishing, as well as biotic invasions, lead to unprecedented biodiversity loss, further affecting the potential of ecosystems to provide ES (Cardinale et al., 2012; Hooper et al., 2012; CBD, 2014). Last but not least, land transformation processes, such as intensification, forestry, grazing and land clearing, induce land use and land cover (LULC) change, which is fundamental for the existence of ecosystems and the provision of ES (Foley et al., 2005).

1.6.2 Scenario approach

The provision of ES is influenced by multiple direct and indirect drivers of both environmental and anthropogenic character, among others including climate change, LULC change and socio-economic changes. Thus, in order to examine potential future provision of ES, it is vital to incorporate these drivers into a consistent framework, robust towards uncertainties.

Estimates of potential future development in various areas (climate, markets, the environment, etc.) are inherently burdened by uncertainties (MA, 2005; Haines-Young et al., 2011). To deal with this issue, multiple approaches have been designed. For instance, simple mathematic trend extrapolations or statistical model projections present the most intuitively understandable examples of such approaches. However, all attempts to project current trends into the future, or to model future development based on current conditions, are inherently encumbered by high levels of uncertainty. Furthermore, trend extrapolations and projections overlook phenomena such as unpredictable abrupt changes, regime-shifts and other traits of complex adaptive systems, making projection prone to misconceptualizations and errors (Rounsevell and Metzger, 2010).

Therefore, a so called scenario approach has been established within both research and practitioners' communities as an alternative method, allowing us to study potential future development from different perspectives. Scenarios present alternative[1] futures, plausible, but also including various types of changes, which may seem improbable from the current perspective but are highly informative in terms of potential future challenges (Figure 3) (Peterson et al., 2003).

Noticeably, among multiple types of scenarios, exploratory and normative scenarios are commonly distinguished (Rounsevell and Metzger, 2010). While normative scenarios analyse pathways leading to certain desired goals, exploratory scenarios aim to "describe future events or developments that are considered possible and can be useful in a process of developing robust strategies design" (Milestad et al., 2014).

In this perspective, exploratory scenarios do not present forecasts of the future; quite the contrary, they are designed as extreme limits between which the real landscape development will probably occur (Rounsevell and Metzger, 2010), aiming to outline potential contrasting trends and extremes, which give the boundaries to probable future development.

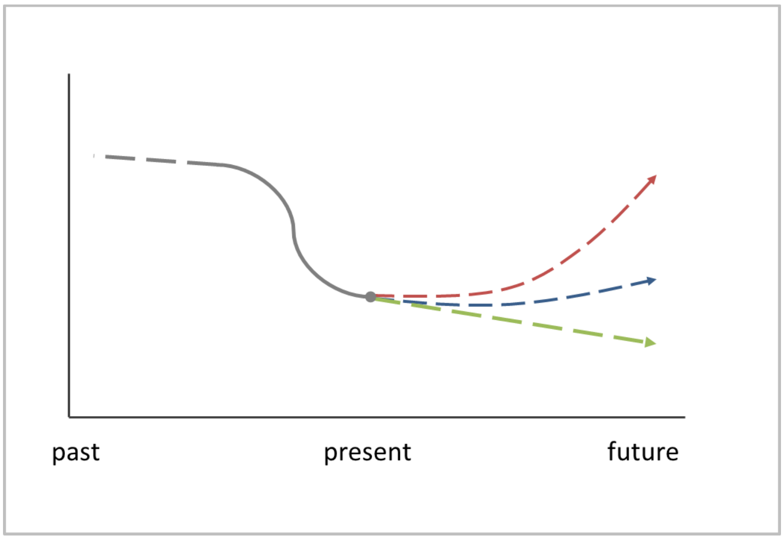


Figure 3. Conceptualization of the scenario approach.
(Source: Author's elaboration)

[1] Unlike in the Czech language, where the term "alternative" generally refers to a choice between *two* options, in English, the meaning of "alternative" refers to two or *more* possibilities (http://www.oxfordlearnersdictionaries.com/), which is widely reflected in international literature on scenarios (Peterson et al., 2003; Nelson et al., 2009; Goldstein et al., 2012). Therefore, we comply with the letter understanding of this term in this thesis.

1.6.2.1 Climate change scenarios

In climate science, scenarios are applied to mitigate extensive uncertainties regarding green-house gas emissions, future radiative forcing of climate change and consequent responses by human society. Thus, the global climate-research community has development several successional arrays of emission scenarios. Such scenarios assume different potential future levels of green-house gas emissions, and serve as the basis for subsequent modelling of radiative forcing and climate change. These scenarios typically incorporate (or are linked to) socio-economic storylines, which may lead to given level of green-house gas emissions (Moss et al., 2010).

The two most recent sets of emission scenarios are represented by scenarios from the Special Report on Emissions Scenarios (SRES) (Nakićenović et al., 2000), used in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007), and the Representative Concentration Pathways scenarios (RCP) (Moss et al., 2010; van Vuuren et al., 2011), utilized in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014). Both series of scenarios have been consecutively used to predict potential future level of climate change, among others in terms of temperature rise (Rogelj et al., 2012).

While each SRES scenario was linked to a specific socio-economic storyline (Nakićenović et al., 2000), leading to a given level of green-house gas emissions and radiative forcing, for the RCP scenarios, a matrix approach was selected (van Vuuren et al., 2014). This approach presumes that each of the radiative forcing levels from different RCP scenarios can be reached by multiple socio-economic pathways, denoted as Shared Socioeconomic Pathways (Kriegler et al., 2014; Neill et al., 2014).

The SRES and RCP scenarios have been repeatedly applied as an input in modelling potential future LULC change. While the LULC scenarios based on SRES emission scenarios (Settele et al., 2005; Dendoncker et al., 2006; Rounsevell et al., 2006; Spangenberg, 2007; Spangenberg et al., 2012) are available for Europe in a fine spatial resolution (see the Methods section for further details), RCP-based LULC scenarios are currently available only at global scale and in a coarse resolution, not eligible for local-scale applications (Hurtt et al., 2011).

1.6.2.2 *Land use and land cover change scenarios*

Many driving forces affecting the provision of ES can be described in terms of LULC change (Verburg et al., 2004; Metzger et al., 2006). Therefore, LULC scenarios are commonly utilized to translate the influence of various human-driven driving forces (Rounsevell et al., 2012) and can serve as the basis for analysing the changes in ES (Bennett et al., 2003).

In the recent literature, evidence of LULC scenario approach applications can be found in multiple studies, including local and regional case studies (Nelson et al., 2009; Goldstein et al., 2012), national scale studies (Verburg et al., 2006) and European-scale arrays of LULC scenarios (Ewert et al., 2005; Rounsevell et al., 2005, 2006; Verburg et al., 2007).

The scenario approach allows depicting plausible LULC development under different intensities of driving forces, and provides the opportunity to compare ES outcomes. Finally, the levels of ES under each scenario can be compared and the resulting trade-offs between scenarios can be easily communicated to public and decision-makers. The approach of LULC scenarios does not strive to make predictions; on the contrary, it aims to create a set of dissimilar alternatives to capture the uncertainty of future development (Rounsevell and Metzger, 2010).

1.7 Research aims and questions

The overarching aim of the thesis was to compile a coherent modelling approach providing a novel perspective on SES dynamics while using the concept of ES, and to test this modelling and participatory methodological approach in selected SES, represented by UNESCO Biosphere Reserves.

First, we aimed to contribute to transdisciplinary research of SESs by developing a methodology to build future LULC change scenarios based on stakeholder engagement. To demonstrate the methodology, two UNESCO Biosphere reserves in the Czech Republic were selected as representative and well spatially defined SES, namely Třeboň Basin Protected Landscape Area and UNESCO Biosphere Reserve (further denoted as Třeboň Basin BR), and Šumava National Park and UNESCO Biosphere Reserve (Šumava BR).

The second aim of this study was to support decision-making related to sustainable landscape management in the case study areas by modelling ES and their trade-offs under various participatory LULC scenarios. Although the case study areas are recognized as spatially protected within the national legislative system, they currently face intensive anthropogenic pressures, demand for natural resources and recreational capacities, which causes substantial ecosystem changes in their most vulnerable localities. The assessment of potential trade-offs between ES for various scenarios aimed to serve as one of the inputs into local landscape decision-making processes.

Finally, we aimed to contribute to the development of LTSER in Czech biosphere reserves by quantifying the impact of anthropogenic driving forces on the provision of ES, employing a combination of approaches from social and natural sciences, namely participatory stakeholder engagement with LULC and ES modelling.

The thesis postulated the following research questions:

1. How to build exploratory scenarios of future LULC change based on combination of quantitative and participatory approaches? Which methods can be applied to (1) conduct a participatory analysis of SES dynamics, and (2) transform the results into future LULC change scenarios?

2. Which combination of spatially explicit modelling approaches can be utilized to assess ES and their trade-offs under future scenarios in a coherent manner? How to coherently quantify ES and predict their future development?

3. What are the synergies and trade-offs in the future provision of ES under different landscape management scenarios in selected case study areas?

These research questions lead to a hypothesis that various future landscape management options generate different outcomes regarding ES provision and trade-offs. As these options are co-defined by natural conditions and stakeholder actions, participatory scenarios and modelling approaches were used to test this hypothesis.

2 Methods

2.1 Research design

Based on the above introduced aims of the study, successive research steps (described in detail in the following sections) were as follows:

1. To assess socio-ecological dynamics in selected case study areas and to identify the most important drivers of ecosystem change, utilizing participatory approaches,
2. To elicit plausible participatory storylines of future landscape development in the study areas,
3. To create an array of exploratory LULC change scenarios based on the participatory storylines, using multiple spatial modelling approaches,
4. To propose a coherent combination of modelling approaches to assess provisioning, regulating and cultural ES for each of the scenarios,
5. To assess potential trade-offs, emerging between different types of ES, under multiple scenarios.

2.2 Study areas

Both case study areas selected for this study present UNESCO Biosphere Reserves and LTSER platforms. LTSER platforms have been established worldwide to enhance the understanding of social-ecological systems and to broaden the scope of traditional long-term ecological research (LTER) beyond its previous limits (Singh et al., 2013). LTSER is able to capture long-term development of social-ecological systems, gradual changes of many variables as well as the interrelations between them (Haberl et al., 2006). In this respect, biosphere reserves have been proposed as sites particularly suitable for LTSER, facilitating to study the sustainability of social-ecological systems and the impact of various socio-economic driving forces on natural ecosystems (Lotze-Campen, 2008). Since ES have been identified as one of the linking elements between natural ecosystems and human society within a social-ecological system, they provide a particularly useful concept for promoting integrated research of social-ecological systems and LTSER in the context of landscape management and governance (Collins et al., 2011).

Among Czech UNESCO Biosphere Reserves and LTSER platforms, Třeboň Basin BR and Šumava BR were selected as case study areas. Since one of the aims of the study was to compile a comprehensive methodology to study social-ecological systems' dynamics and to assess multiple types of ES under future scenarios, it was necessary to select a sample of case-study areas covering multiple types of social-ecological systems and providing an illustrative range of ES types. The selected biosphere reserves present different types of social-ecological systems, with diverse landscape character and distinct prevalent types of use, thus providing mutually complementing sets of ES. At the same time, both areas face intensive anthropogenic pressures with unclear landscape development perspectives to the future, which makes the outcomes of local socio-ecological research particularly relevant for local landscape-planning and decision-making agendas.

In this thesis, we developed a coherent methodology to assess ES trade-offs, and subsequently illustrated this methodology on a sample of SES, which were representative in terms of landscape and ES diversity. Thus, we did not aim to compare the two selected case study areas, but rather to conduct their parallel analysis with the application of the same methodological framework in different conditions.

2.2.1 Třeboň Basin Biosphere Reserve

Třeboň Basin is located in the south of the Czech Republic (49° 00' 13.0961"N, 14° 46' 14.3378"E), covering an area of 700 km^2, with an altitude between 410 and 550 m above sea level (Figure 4). The mean annual temperature is approximately 7°C and annual precipitation varies between 600 and 650 mm (Tolasz, 2007). The study site is located in a flat, semi-natural landscape, most distinctively characterized by coniferous forests, wetlands, wet meadows and artificial water reservoirs (fish ponds) (Figure 5). According to CORINE Land Cover 2006 (EEA, 2007), coniferous forests occupy 45% of the study site, followed by agricultural land (25%), pastures (11%) and water bodies (7%) (Figure 6).

Since the 15th century, Třeboň Basin landscape has been modified by human activities, primarily fish-farming, and it has been highly valued due to its natural and cultural assets. Třeboň Basin was designated UNESCO Biosphere Reserve and LTER site in 1977 and several local fishponds and peat lands have been designated as wetlands of international importance under the Ramsar Convention on Wetlands. In addition, it was declared as Protected Landscape Area (PLA) at the national level in 1977. Třeboň Basin area has an extensive record of research, including biodiversity, ecology of ecosystems and traditional discussion between different stakeholders dating back to the 1970s (Jeník and Přibyl, 1978; Pokorný et al., 2000).

Although Třeboň Basin was declared PLA, several exploitive activities are still permitted within its boundary as a legal consequence of previous protection regimes. At the same time, it draws the interest of several businesses due to the economic potential of local natural resources. Therefore, Třeboň Basin presently faces potential threats from a complex of human activities, such as intensive fish-farming, sand and gravel mining, and biogas energy production (which serve as an energy supply for spas in Třeboň). The main impact of fish-farming, practiced in nearly five hundred fishponds ranging between 0.1 and 700 hectares, is intensive fertilization. Subsequent effects include pond eutrophication, excessive development of algae and cyanobacteria, extreme fluctuation of oxygen levels and nutrient loading to surrounding landscape, leading to decrease in productive and recreational potential of the landscape (IUCN, 1996). Sand and gravel mining concentrates along water courses and threatens to affect some of the most valuable local ecosystems. Regarding the impact of agricultural use on local landscape, potential increase in intensive farming practices including the application of pesticides and fertilizers would jeopardize the endeavour to conserve local biodiversity levels and ecosystem processes. Beside fish-farming and agriculture, Třeboň Basin is an important destination for tourism and recreation, which presents another source of pressure on this vulnerable area. In sum, the study area faces the question whether to sustain current levels of landscape protection, or to promote economic growth counterbalanced by potential decrease in the provision of ES.

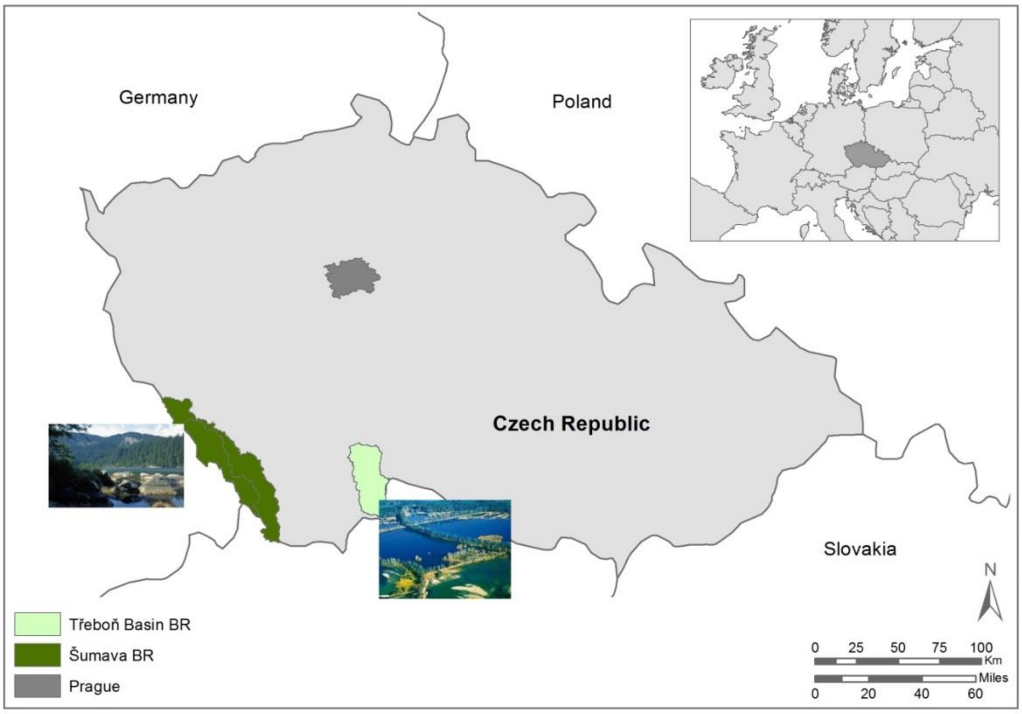


Figure 4. Localization of two case-study UNESCO Biosphere Reserves, Třeboň Basin BR and Šumava BR (based on data by AOPK ČR).
(Source: Author's elaboration)

Figure 5. Landscape character of Třeboň Basin UNESCO Biosphere Reserve
(Source: Miroslav Hátle)

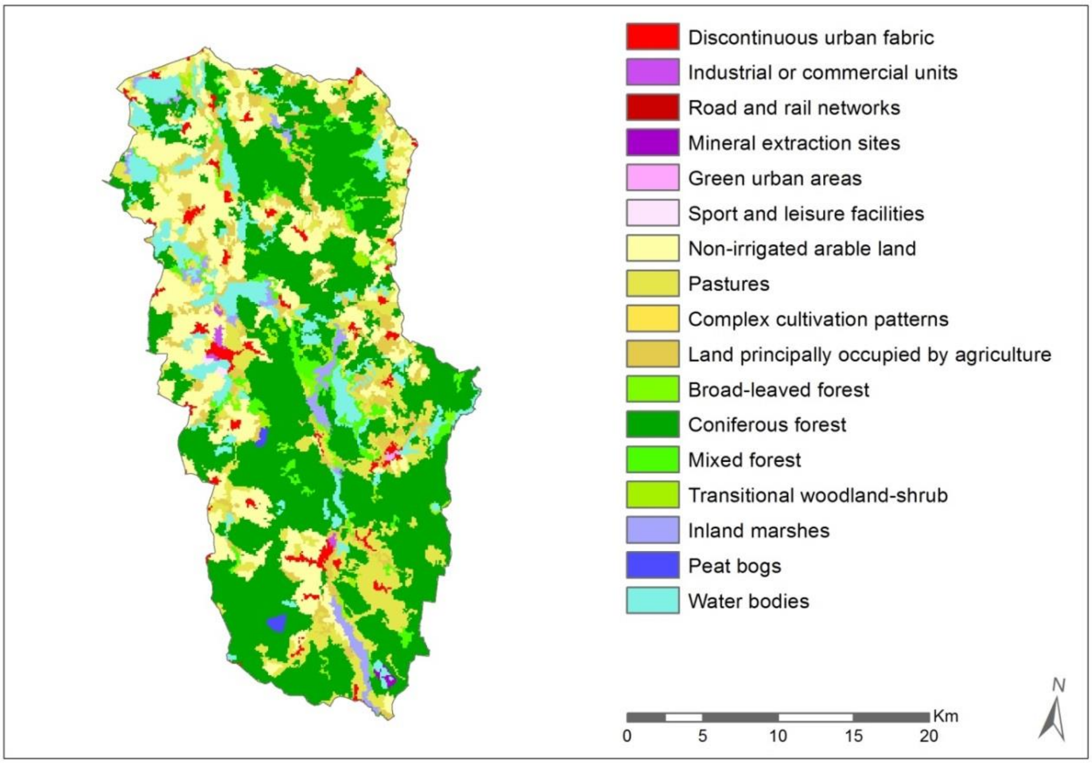


Figure 6. The land use and land cover of Třeboň Basin BR (based on CORINE Land Cover 2006).
(Source: Author's elaboration)

2.2.2 Šumava Biosphere Reserve

The Šumava Mountains (49°01'26.6300" N, 13°29'57.5362" E), located in the south of the Czech Republic, present one of the most ecologically valuable forested montane ecosystems in Central Europe (Figure 4, Figure 7). According to CORINE Land cover 2006 (EEA, 2007), local landscape comprises mainly near-natural and semi-natural coniferous forests (59%), pastures (14%), marshes and peat-bogs (2.4%), and glacial lakes (Figure 8). The most pristine area of the Šumava Mountains has been protected since the 1960s and declared National Park (NP) in 1991, surrounded by a buffer zone of the PLA. Both the NP (680 km^2) and the PLA (996 km^2) comprise Šumava UNESCO Biosphere Reserve.

Figure 7. Landscape character of Šumava UNESCO Biosphere Reserve
(Source: Josef Brůna)

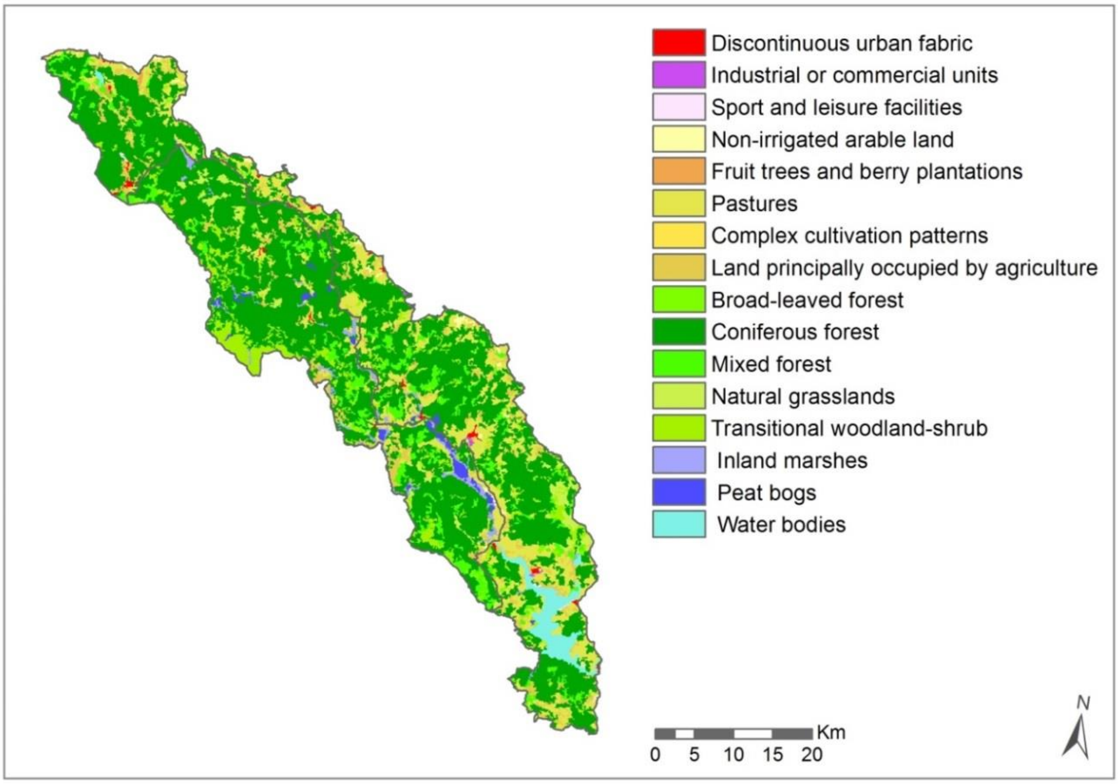


Figure 8. The land use and land cover of Šumava BR (based on CORINE Land Cover 2006).
(Source: Author's elaboration)

In order to capture broader context of the area, this study focused on Šumava UNESCO Biosphere Reserve, not solely on the area of the NP. The study area is situated between 467-1378 meters above sea level (m a.s.l.), with average temperatures approximately 6°C in 750 m a.s.l. and 3°C in 1,300 m a.s.l. The average annual precipitation varies between 800 and 1550 mm, while average annual potential evapotranspiration reaches approximately 450 mm (Tolasz, 2007). The study area comprises 32 municipalities, out of which only 10 reach over 500 inhabitants. The area struggles with decreasing population and increasing average age of the inhabitants in local municipalities in the long term (Novotná and Kopp, 2010; Perlín and Bičík, 2010). An extensive artificial water reservoir (Lipno) is located in the southern part of the study area, contributing to numerous benefits including drinking water, hydropower and recreational opportunities.

Together with the neighbouring Bavarian Forest NP in southeast Germany, Šumava NP covers one of the largest forested areas in central Europe, providing a wide array of ES and high biodiversity levels. The area provides habitats for numerous threatened species such as lynx (*Lynx lynx*) and capercaillie (*Tetrao urogallus*) and contains several sites of pristine Norway spruce (*Picea abies*) forests in higher altitudes. The majority of local habitats are not influenced by human settlements, since most of the former German-speaking inhabitants were expelled after the World War II and the area became a part of the abandoned border zone (Novotná and Kopp, 2010). Šumava NP has been recognised by the International Union for Conservation of Nature (IUCN) (category II – National Park) and reflected in several international conventions, e.g. Ramsar Convention designating the most pristine peat-bogs as wetlands of international importance. Šumava NP is also a part of the Natura 2000, a network of sites protected within EU biodiversity and conservation policy directives.

Šumava is covered by the most extensive forest ecosystem in Central Europe; however, the natural composition of the originally mixed beech, pine and spruce forest has been altered, and at present, semi-natural spruce plantations prevail in most of the area. Non-native spruce varieties were planted in several locations as a result of human demand for fuelwood and timber (for glass industry in the past). Spruce *(Picea abies)* vegetation is not well adapted to local climate and has been susceptible to a range of disturbances such as strong winds and bark beetle (*Ips typographus*) outbreaks (Kindlmann et al., 2012).

LULC change have been moderate in the past two decades in the study area due to its declaration as NP. However, intensive tourism and forestry demand has resulted in increasing LULC change, represented mainly by urbanization and changes in forest management. Both of these changes are limited as the area of the NP is strictly protected. Nevertheless, recent windstorms (in 2007 and 2011) and subsequent bark beetle outbreaks resulted in intensive logging and have given rise to strong discussions about the best management approach and the extent of protected areas in the NP (especially non-intervention zones). At the same time, there are numerous development plans intending to build large-scale touristic resorts, which might change the current level of construction in both qualitative and quantitative ways (EIA Servis, 2011).

Since the establishment of the NP, the concept of the area's management has been repeatedly changing, which has resulted in several substantial changes in zonation and conservation approaches. The management of the NP is subject to several disputes, especially between the administration of the NP, environmental groups and non-governmental organizations, scientists and local interest groups, including representatives of municipalities and businesses. The park is split into three zones: Zone I is the most pristine and strictly protected part of the NP, Zone II includes the near-natural ecosystems that were variously influenced by human activities in the past, and Zone III has areas which enable a wide variety of socio-economic activities (Figure 9). Zones I and II present an equivalent to core zones under Czech legislation. At present, Zone I of the NP consists of several small-scale and disconnected patches, scattered around the area of the NP, while some of them are partly non-interventionist. Currently, the legislation designing the NP is being revisited within the process of adjusting the vision of the NP for the future (Bláha et al., 2012; Křenová and Hruška, 2012).

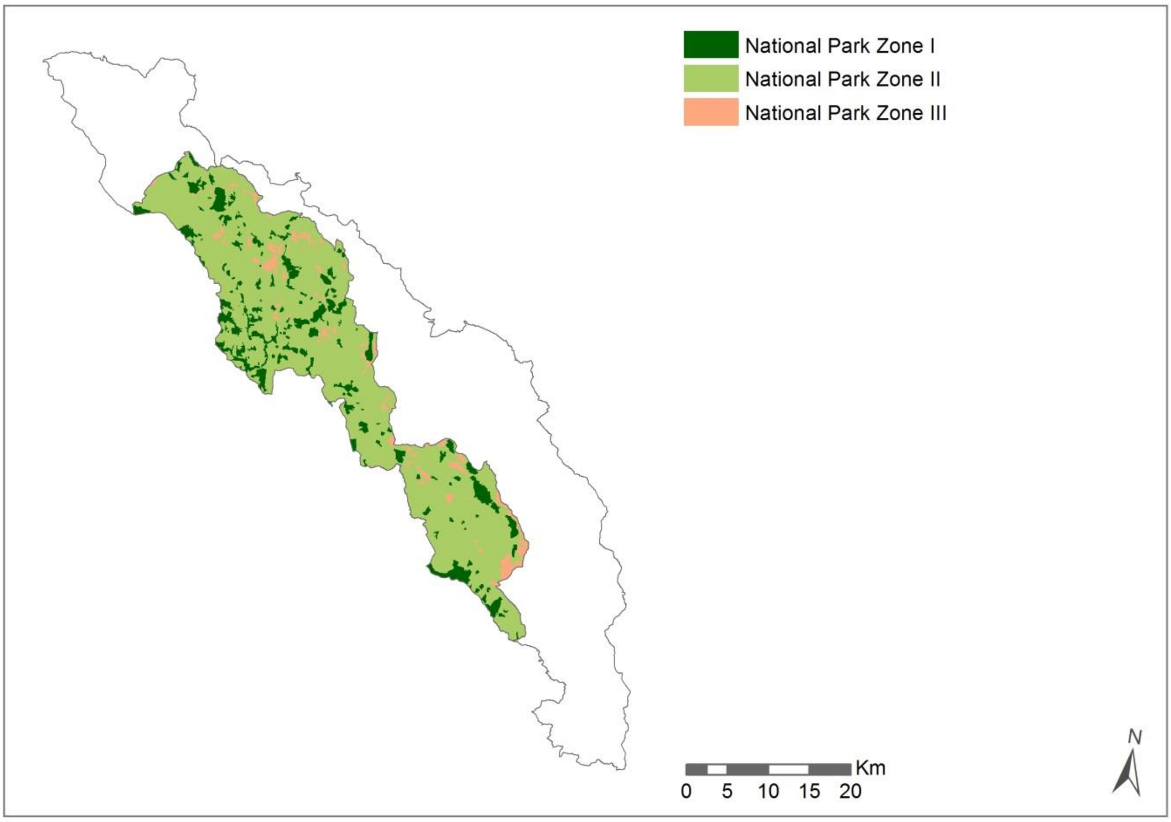


Figure 9. The zonation of Šumava NP (based on data by AOPK ČR).
(Source: Author's elaboration)

2.3 Participatory scenario building

The aim of the first part of the study was to create exploratory scenarios of how the landscape in the case study areas might develop in the medium-term future (2050), in order to subsequently use these as a basis to assess what is the potential impact of different landscape changes on the provision of ES and the trade-offs between them. Furthermore, we aimed to elicit which ES local stakeholders find fundamental in the case study areas, in order to focus on these services in the subsequent analysis.

By the use of exploratory scenarios in this study, we aimed to find probable boundaries of future landscape development and to assess the provision of ES within the interval defined by these boundaries (Goldstein et al., 2012; Lorencová et al., 2013).

Furthermore, we aimed to build scenarios which would capture both the locally-specific landscape dynamics and broader-scale trends in landscape change. To do so, we applied an approach combining participatory and GIS approaches, compiling participatory input from local stakeholders in both study areas with European-scale scenarios, as described in the following sections.

We would like to emphasize that in this study, we did not aim to conduct a sociological survey. Quite the contrary, we aimed to apply the approach of participatory planning, nested in sustainability science and SES studies, in order to elicit stakeholders' knowledge of the dynamics of SESs, and to identify their opinions and priorities regarding future landscape development through individual and group discussions, interviews and exercises (Reed, 2008; Termorshuizen and Opdam, 2009; EEA, 2012; Fagerholm et al., 2013; Celio et al., 2015).

Stakeholder engagement presents a fundamental part of social-ecological research (Reed, 2008). Nevertheless, it is encumbered by numerous issues, such as ensuring the engagement of all key stakeholder influencing the study areas, as well as achieving sufficient participation rates. For both of the case studies, specific issues regarding stakeholder involvement are addressed in the following respective sections and further elaborated in the Discussion section.

2.3.1 Třeboň Basin Biosphere Reserve

To create a series of scenario storylines, characterizing the most important driving forces and their impact on local landscape and ecosystems, we applied the approach of participatory scenario building and collaboration with local stakeholders (Peterson et al., 2003; Reed et al., 2013). In the initial stage of the study, we identified local stakeholders either substantially influencing the land use regime in Třeboň Basin, or having an expertise in the driving forces forming the landscape of the case study area. The main stakeholders involved in the study were chosen to represent industrial, agricultural and touristic sectors (a bio-gas power plant company, Třeboň city spas and two private mining companies), nature protection (Administration of Třeboň Basin PLA), as well as scientific and educational institutes conducting research in the study area (Table 2).

The involvement of research institutions supplemented the absence of several stakeholders, who refused to participate in the scenario building process. Specifically, it was not possible to involve the representatives of local fishing industry (Rybářství Třeboň, a.s.) and forestry representatives (Lesní správa Třeboň, Lesy České republiky, s.p.). Thus, we elicited plausible trends in these sectors from researchers involved in local hydrological, ecological and landscape research.

In total, 17 stakeholders were addressed to participate in the research. Since especially the participants from universities and research institutes showed a high response rate, we eventually gained 14 participants. Due to research funding limitations, it proved unfeasible to organize group scenario building workshops in Třeboň Basin BR case study. Therefore, we applied the approach of semi-structured interviews and individual discussions with the participants.

Table 2. A list of stakeholders involved in the process of participatory scenario building in Třeboň Basin BR.

Sector	Institute/Agency
Nature protection	The Administration of Třeboň Basin PLA
Industry	BIOPLYN Třeboň spol. s.r.o.
	Českomoravský štěrk, a.s.
	LB MINERALS, s.r.o.
Tourism and recreation	Třeboň Spas
Research and education	University of South Bohemia in České Budějovice
	Czech University of Life Sciences Prague
	ENKI, o.p.s.
	Daphne
	Global Change Research Institute CAS

The participatory scenario building was conducted through a series of semi-structured interviews and organized discussions with stakeholders, who were asked to identify driving forces most characteristic and important for local landscape from their professional perspective and their field of expertise. Subsequently, it was elicited how these driving forces influence the study landscape at present, and how they might be potentially expressed in the future. Finally, the stakeholders were asked to describe how they assume the landscape might develop in the medium-term future (2050) and what would be their preferences in terms of landscape development from their professional perspective.

The results of the interviews were grouped based on the dominant topics identified, and subsequently clustered into several coherent scenario-storyline narratives, namely the Market storyline, the Exploitation storyline, the Business-as-Usual (BaU) storyline, the Conservation storyline and the Biofuels storyline (see the Results section).

2.3.2 Šumava Biosphere Reserve

Similarly, the first step in Šumava BR was to elicit local stakeholders' preferences regarding possible future development of the area, the level of nature conservation and economic development. Since the number of stakeholders involved in landscape development in this study area was higher than in the case of Třeboň Basin BR, it was decided to use the approach of participatory scenario building workshops, instead of individual interviews and discussions.

Hence, two participative workshops were organised for various groups of stakeholders, covering all key sectors in the area and representing a broad range of perspectives (Table 3). The workshops aimed at participative scenario building, i.e. creating visions of future development of the study area by developing a series of storylines describing potential future development of the study area through 2050. In the first round, we addressed 20 selected stakeholders; however, we had to address another 10 stakeholders in the second round due to a low response rate, eventually gaining 15 attendees.

Table 3. A list of stakeholders involved in the process of participatory scenario building in Šumava BR.

Sector	Institute
Local authorities	Mayors of the municipalities in the South Bohemian Region
Regional development	Regional Development Agency of Šumava Region
Conservation	The Administration of Šumava NP
Research and education	University of South Bohemia in České Budějovice
Energy	Representatives of local energy production agency
Water management authorities	The Vltava Catchment
Agriculture	Representatives of local private agricultural enterprises
Tourism and recreation	Local guides and representatives of private touristic enterprises

Since we were aware that the idea of scenario building would be rather unfamiliar for the stakeholders, the workshops started with introductory presentations explaining the concept of future scenarios and participative scenario building (Metzger and Rounsevell, 2010; Rounsevell and Metzger, 2010). Following the introduction, the stakeholders were involved in an array of sub-group discussions and interviews. They were asked to follow a list of key economic sectors and issues characteristic of the area (demographic and economic development, tourism and recreation, agriculture, water management, nature conservation, etc.), and to formulate their preferences and expectations regarding each of the topics. They were also encouraged to add their own insight and issues of interest into the storylines. Due to the substantially different backgrounds of the stakeholders involved, we did not insist on reaching a consensus on a single vision among all stakeholders, but recommended trying to come to an agreement on one vision per stakeholder group. Eventually, the stakeholders identified three storylines denoted as the Green scenario, the Red scenario and the Shared vision (see Results). Stakeholders' input thus resulted in an array of narratives, which were further translated into LULC change scenarios using GIS approaches.

2.4 Land use and land cover change scenarios

Since our aim was to further utilize the scenarios of landscape development for the assessment of ES, it was necessary to translate the scenario storylines, created during participative scenario workshops and interviews, into spatially explicit LULC scenarios, describing specific changes in landscape composition and configuration, which would subsequently serve as an input into ES modelling. Furthermore, we aimed to connect the stakeholder storylines with data on larger-scale landscape dynamics.

Therefore, we combined current LULC datasets (CORINE Land Cover; EEA, 2007), European-scale dynamic LULC change scenarios (ALARM; Settele et al., 2005) and stakeholder input from the previous parts of the study, using methods of spatial modelling available through the ArcGIS platform (ESRI, 2013). The conceptual framework of this approach is outlined by Figure 10 and its components and steps are introduced and elaborated in the next sections.

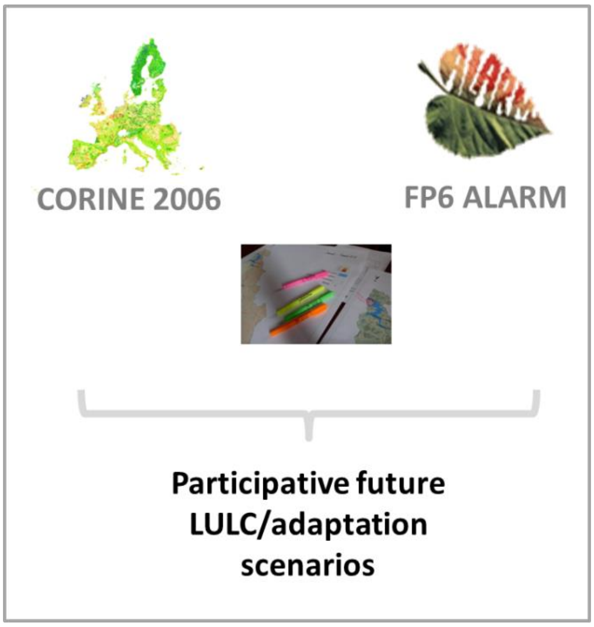


Figure 10. Conceptual framework of the modelling process applied to build an array of land use and land cover change scenarios for two case study areas
(Source: Author's elaboration)

2.4.1 CORINE Land Cover

CORINE Land Cover (CLC; EEA, 2007) datasets are freely available European maps of LULC, provided by European Environment Agency. CLC categorizes different LULC types into 30 classes in the Czech Republic, of which 18 were present in our study sites. The resolution of CLC corresponds to a map scale of 1:100,000 and the datasets are based on a minimum mapping unit of 25 ha. The CORINE Land Cover category classification was used to distinguish LULC types in this study and was maintained in all scenarios.

2.4.2 ALARM scenarios

The European scale LULC change scenarios used to incorporate European-scale landscape dynamics in this study were ALARM scenarios, developed within the 6th Framework Programme ALARM project (Assessing Large-scale environmental Risks for biodiversity with tested Methods) (Settele et al., 2005; Rounsevell et al., 2006). These dynamic LULC scenarios were originally developed to project the impact of social and economic pressures on biodiversity in Europe, reflecting major European-wide socio-economic and environmental trends. Subsequently, to enable use in national to regional studies, the scenarios were downscaled to a country-specific level in the Ecochange project (Challenges in assessing and forecasting biodiversity and ecosystem changes in Europe;

Dendoncker et al., 2006). At present, the ALARM scenarios present the only available comprehensive set of European-level scenarios with a fine spatial resolution (100 m x 100 m grid cell).

In terms of climate change characteristics, each of the ALARM scenarios is linked to a specific IPCC SRES emission scenario, with corresponding climate change projection (Nakićenović et al., 2000) (Table 4).

As an input into this study, we used three ALARM scenarios, incorporating a broad range of social, economic, political and geo-biosphere parameters, which are reflected in LULC changes in several time slices including 2020, 2050 and 2080 (Rounsevell et al., 2006; Spangenberg, 2007; Spangenberg et al., 2012). The main characteristics of the three ALARM scenarios used in this study are summarized below and in Table 4.

1. Business As Might Be Usual (BAMBU) presents a scenario extrapolating the expected socio-economic trajectories in EU decision making and policy, based on current knowledge, and assessing their potential impacts on sustainability and biodiversity. This scenario thus assumes that policy decisions already made in the EU will be implemented and enforced, while potential new ones will follow the same development path. Thus, it should be noted that BAMBU does not present a business as usual (BAU) scenario, based merely on extrapolation of past trends. At the national level, deregulation and privatization continue except for "strategic areas". Internationally, free trade is the overarching principle. Environmental policy is approached mainly from a technological perspective, focusing on tackling challenges by innovation, market incentives and legal regulation, resulting in a mix of market liberalism and socio-environmental sustainability policy.

2. GRowth Applied Strategy (GRAS) presents a liberal, growth-focused scenario, describing a world based on economic principles such as the prevalence of the market, free trade and globalization. The primary means of implementation is deregulation (with certain limits), while economic growth presents a key objective, actively pursued by politics and governments. The scenario policies show limited interest in social and institutional sustainability; economic sustainability is interpreted mainly as economic growth. Environmental policy focuses mainly on damage repair, while the scale and scope of preventive actions

is designed solely based on cost–benefit calculations. Measures for biodiversity protection (and other environmental problems) are limited and are only taken retroactively, when problems emerge. Regarding climate change, GRAS focuses on adaptation rather than mitigation, with some measures taken to limit climate change.

3. Sustainable European Development Goal (SEDG) presents a normative scenario, i.e. a scenario designing a course of development necessary to reach a certain target. In this case, SEDG focuses on achieving socially, environmentally and economically sustainable development. Policy priorities under SEDG include halted biodiversity loss, a competitive economy and a healthy environment, gender equity and international cooperation. SEDG presents a precautionary approach, aiming to take measures regardless the uncertainty, in order to avoid not yet fully known future damages.

Table 4. Summary of the ALARM scenarios in terms of EU policy targets (according to Spangenberg et al., 2012).

Scenario	GRAS	BAMBU	SEDG
Climate projection	Corresponds to the IPCC SRES **A1FI** storyline and its assumptions	SRES **A2** (the best fitting SRES scenario available at the time of calculation, though SRES A1B would have fitted better to past emission trajectories)	SRES **B1** (SRES scenario with the lowest emissions, but not as low as 450 p.p.m. CO_2 stabilization assumed so the SEDG storyline differs significantly from B1)
EU Common Agricultural Policy	Dismantling payments for **production** (1st pillar) and for **rural development and environment** (2nd pillar)	Shift from 1st to 2nd pillar results in polarisation: intensification of high yielding locations, neglect of low yielding ones	Spatially explicit support structure to maintain (organic) agriculture throughout the landscape (only the 2nd pillar transfers remain)
EU funds	Phasing out, considered as subsidies	Focused on infrastructure development and growth in poor regions	Focused on local green development and opportunities, education and employment
Energy policy	Efficiency, some renewable energies based on cost	Efficiency, aiming at 20% reduction of greenhouse gas	Aiming at 75% reduction of CO_2 emissions by 2050

Scenario	GRAS	BAMBU	SEDG
	calculations	emissions by 2020, 80% by 2080. Increase in nuclear and renewable energy	through savings, changing consumption patterns and renewable energies
Transport policy	Increased efficiency due to market pressure, no policy to shift the modal split or even reduce transport	Technological improvements and change in share of different modes of mobility (walking, cycling, trains, cars, boats, planes) – modal split	Transport reduction priority, plus modal split change (through pricing and infrastructure supply), technical improvements
EU chemicals policy: REACH*	Focus on innovation and competitiveness	REACH implemented	REACH plus; filling gaps, e.g. for nano-materials, endocrine disruptors, metals.
Trade policy	Strong support for World Trade Organization and free trade	Promoting free trade except in "strategic areas"	Global sourcing/transport of goods reduced for cost reasons; phytosanitarian controls

*REACH – Registration, Evaluation, Authorization and Restriction of Chemical Substances

2.4.3 Stakeholder input

In order to translate stakeholder storylines into spatially explicit LULC change scenarios, each scenario-storyline narrative developed by the stakeholders was transformed into a hierarchy of LULC change priorities. These priorities described which types of LULC are more probable to be replaced by other types in the future under different scenarios, and vice versa, which types of LULC will probably remain in their original extent or expand.

For the scenario storylines assuming high levels of nature protection (the Conservation scenario in the case of Třeboň Basin BR and the Green scenario in the case of Šumava BR), the LULC priority hierarchy was as follows:

$$(p_f;\ p_{pb};\ p_{wb};\ p_w) > (p_b;\ p_p;\ p_{pa}) > (p_a;\ p_m) \quad (1)$$

where p_f represented the priority of forest LULC category, p_{pb} represented the priority of peat-bogs, p_w the priority of wetlands and p_{wb} the priority of water bodies. Similarly, p_b represented the priority of built-up areas, p_p the priority of pastures and p_{pa} the priority of land principally occupied by agriculture. Finally, p_a represented the priority of arable land and p_m the priority of mining sites. Furthermore, all mining sites were transformed to water bodies in this scenario as a result of potential restoration measures.

The storylines assuming moderate changes in the landscape, corresponding with the current landscape trends (the BaU scenario in Třeboň Basin BR and the Shared vision in Šumava BR), were characterized by the following priority hierarchy, generally preserving current LULC patterns:

$$(p_b;\ p_f;\ p_w) > (p_a;\ p_w;\ p_{pb}) > (p_p;\ p_{pa};\ p_m) \quad (2)$$

The group of storylines assuming high level of exploitive anthropogenic activities (the Exploitation scenario in the case of Třeboň Basin BR and the Red scenario in the case of Šumava BR), the LULC hierarchy prioritized built-up areas, mining sites and intensively managed agricultural land over extensively managed agricultural areas, wetlands, peat bogs and forests:

$$(p_b;\ p_m;\ p_a;\ p_w) > (p_{pa}) > (p_p) > (p_w;\ p_{pb};\ p_f) \quad (3)$$

Furthermore, in Třeboň Basin BR case study, all prospective mineral extraction sites were considered as realized in the Exploitation scenario and replaced the current LULC, since the local stakeholders assumed an intensification of mining activities in the study area in this storyline, due to expected increasing demand for sand and gravel for potential construction of extensive strategic infrastructure (e.g. power plants, dams) in the Czech Republic in the forthcoming decades. The data on potential mining sites in the study area were provided by the Czech Geological Survey. In this scenario, pastures (p_p) were transformed to land principally occupied by agriculture (p_{pa}), due to an increasing local demand for agricultural products, e.g. corn, as a raw material for biogas production. Similarly, peat bogs (p_{pb}) were assumed to be intensively utilized and finally transformed into water bodies as a restoration approach (p_w).

For the Market and the Biofuels scenarios in Třeboň Basin BR, the storylines were fully in line with the original ALARM scenario storylines; therefore, in the Market scenario, the highest prioritized LULC types were forests (p_f) and built-up areas (p_b), replacing transitional woodland-shrub (p_{ws}) and non-intensive agricultural areas (p_{pa}; p_p) (equation (4)). The Biofuels scenario prioritized arable land (p_a) for biofuels production against all other agricultural LULC types (p_{pa};p_p). Furthermore, as a result of sustainable forest management, transitional woodland-shrub (p_{ws}) was assumed to be replaced by forests (p_f) (equation (5)).

$$(p_f;\ p_b;\ p_w) > (p_a) > (p_{pa};\ p_p;\ p_{ws}) \tag{4}$$

$$(p_b;\ p_a;\ p_w) > (p_{pa};\ p_p;\ p_f) > (p_{ws}) \tag{5}$$

The priority of water bodies (p_w) remained in the higest group in all scenarios, since the extent of this land cover type was not assumed to change in the future.

2.4.4 Modelling process

In order to combine the above introduced European-scale dynamic LULC scenarios with stakeholder inputs, we followed a modelling approach outlined in Figure 11 using the ArcGIS platform (ESRI, 2013).

1. First, we overlaid the ALARM 2050 LULC scenarios with CORINE Land Cover 2006 at 100 x 100 m resolution and identified all changed raster grid cells, their initial LULC category and the final LULC category.

2. Second, we grouped all cells characterized by different character of LULC change (e.g. forests to grasslands, grasslands to built-up) into separate datasets.

3. These individual cell-change datasets were then combined with the LULC change priority hierarchies derived from stakeholder storylines. In this step, the LULC change trends identified by the stakeholders as highly improbable in the study area were removed from the LULC change database; on the contrary, we supplemented each cluster by locally specific trends proposed by the stakeholders.

4. Based on the storyline hierarchies, the cell-change databases were simultaneously grouped into several clusters of LULC changes, corresponding to individual storylines.

5. Finally, we used each change cluster as an update to CLC2006, gaining an array of participatory LULC scenarios to 2050 corresponding to stakeholder storylines.

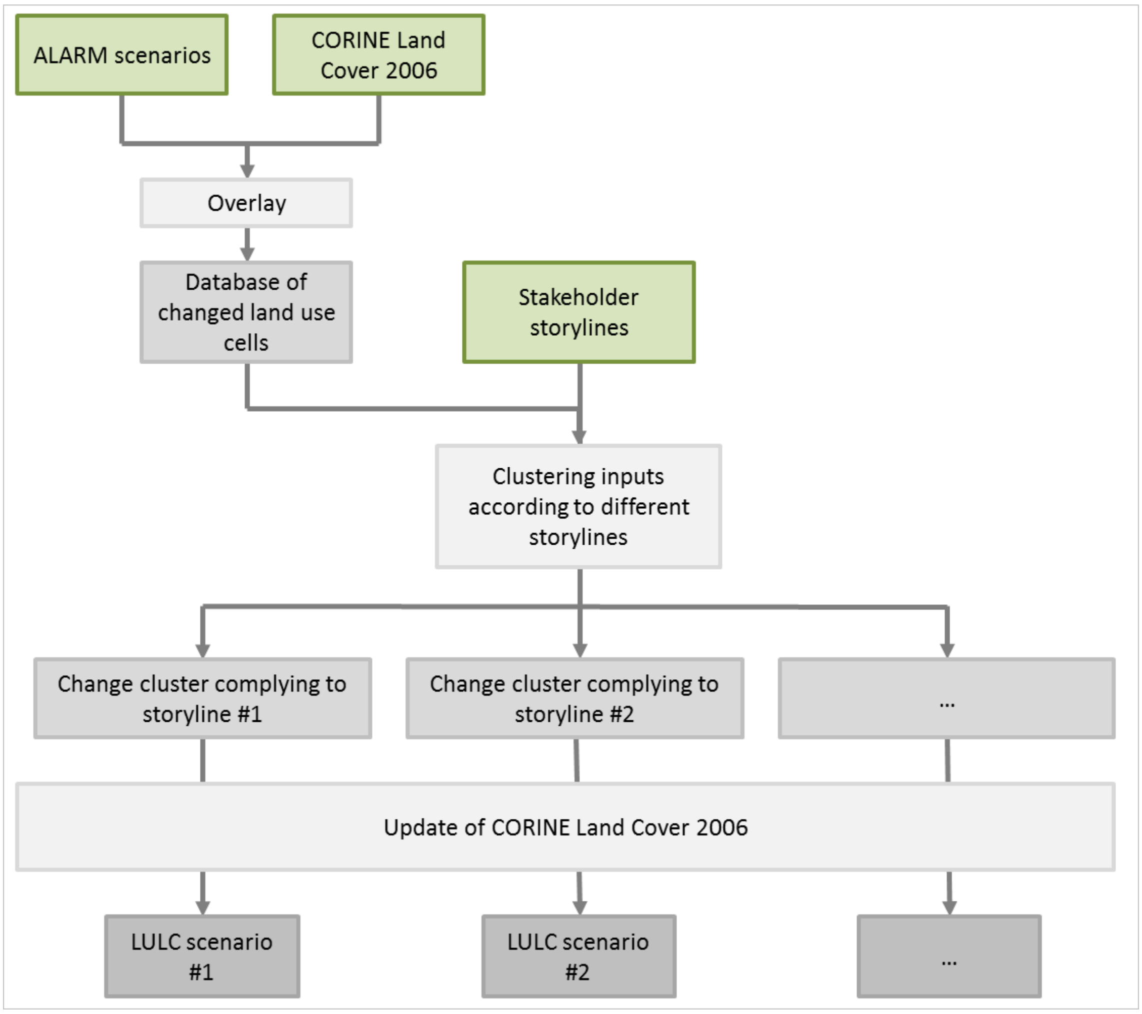


Figure 11. The framework for the modelling of land use and land cover change scenarios
(Source: Author's elaboration)

Each participatory LULC scenario built in this study was partially based on one specific ALARM scenario, which, in turn, was originally derived from a certain IPCC SRES emission scenario (see section 2.4.2 and Table 4). For instance, the BaU scenario for Třeboň Basin BR was derived from the ALARM BAMBU 2050 scenario, which, in turn, is based on the A2 SRES scenario. Therefore, there is a direct connection of each of the participatory LULC scenarios in this study to a certain SRES emission scenario. For instance, the Market scenario complies with the A1FI SRES scenario, the Biofuels scenario complies with the B1 SRES scenario, and all other scenarios in this study comply with the A2 SRES scenario (Table 5).

Thus, each of the participative LULC scenarios created in this study assumes a specific emission level of green-house gases and corresponding development of climate parameters. To take this into account during the modelling of ES (especially water-related ones), it was necessary to pair each participatory LULC scenario in this study with a corresponding climate projection. In optimal case, such a climate projection for each participative scenario should be based on the same or similar greenhouse-gas emission levels as the scenario's source SRES. In order to achieve this goal, we utilized climate projections based on Representative Concentration Pathways scenarios, developed by IPCC for its Fifth Assessment Report and presenting the most current version of widely accepted emission scenarios (Moss et al., 2010; van Vuuren et al., 2012). In this study, we utilized climate projections based on RCP4.5 and RCP8.5 emission scenarios (Table 6), provided by Global Change Research Institute CAS, v.v.i, resulting from climate modelling with the Aladin-CLIMATE/CZ model for the area of the Czech Republic (Štěpánek et al., 2009, 2011).

Specifically, participative scenarios based on A1F1 scenario were paired with RCP8.5 climate projections, while the scenarios based on A2 and B1 were paired with RCP4.5 scenarios based on available comparative studies (Rogelj et al., 2012). For a detailed list of combinations between LULC change scenarios and RCP-based climate projections used in this study, see Table 5.

Table 5. Combinations between participative scenarios, ALARM scenarios, SRES scenarios and RCP scenarios applied in this study.

Participative scenario	ALARM	SRES	RCP
Market	GRAS	A1FI	RCP8.5
Exploitation	BAMBU	A2	RCP4.5
BaU	BAMBU	A2	RCP4.5
Conservation	BAMBU	A2	RCP4.5
Biofuels	SEDG	B1	RCP4.5
Green	BAMBU	A2	RCP4.5
Shared vision	BAMBU	A2	RCP4.5
Red	BAMBU	A2	RCP4.5

Table 6. Parameters of the baseline climate (2006) and climate change projections to 2050 based on RCP4.5 and RCP8.5 applied in this study (at the scale of the Czech Republic).

	Baseline (2006)	RCP4.5 (2050)	RCP8.5 (2050)
Average annual temperature			
Average	8.1	9.8	10.3
Minimum	1.3	2.8	3.3
Maximum	10.7	12.3	12.8
Average annual precipitation			
Average	690	760	770
Minimum	390	450	490
Maximum	1900	1990	2050

2.5 Ecosystem services assessment

The main aim of this study was to assess the ES provided by the case study landscapes under different scenarios, together with their potential trade-offs. For this purpose, the LULC scenarios developed in the previous steps were used as an input into a biophysical assessment of selected ES.

As we recognize the heterogeneity in the conceptualizations of ES provision and related terminology (Villamagna et al., 2013), for the purposes of this study we define the provision of ES as the capacity of landscape to generate goods and benefits which contribute to human well-being, in accord with (Kareiva et al., 2011).

In the selection of ES for the analysis, we followed several priorities. First, we focused on ES identified as crucial in the case study areas by the stakeholders during participative scenario building. Second, we aimed to assess a balanced sample of provisioning, regulating and cultural services, to ensure a non-biased input into the analysis of trade-offs between different types of ES. Third, we aimed to assess a sample of globally and locally beneficial services, such as climate regulation on the one hand and nitrogen retention from run-off water on the other.

The final selection of ES and their relevance for the study areas was as follows:

1. Třeboň Basin BR:

    a. Crop production: Agricultural production relevant both locally and regionally; furthermore, local agricultural production serves as an input into local bio-gas generation in Třeboň;

b. Timber production: Forestry production utilized both locally and regionally;

c. Climate regulation: Extensive forests in the study areas serve as a carbon sinks and contribute to climate change mitigation;

d. Water quality regulation in terms of nitrogen and sediment retention: Relevant for numerous water reservoirs and fish-ponds in the study area. In Třeboň Basin, water reservoirs are exclusively assigned to fish production and are characterized by high levels of fertilizer input. Since the water from reservoirs is periodically discharged during pond fishing, the downstream landscape suffers from excessive loads of phosphorus and nitrogen (IUCN, 1996);

e. Recreation potential: Relevant for the tourism and recreation sector as an important source of economic revenues in the area.

f. Landscape aesthetics: Relevant as the non-tangible benefits enhancing the well-being of local citizens, visitor and tourists.

2. Šumava BR:

    a. Hydropower production: Local water yields contribute to the Lipno reservoir, which hosts two hydro-power plants;

    b. Climate regulation: Extensive forests in the study areas serve as a carbon sinks and contribute to climate change mitigation;

    c. Water quality regulation in terms of nitrogen and sediment retention: Relevant for the Lipno water reservoir;

    d. Recreation potential: Relevant for the tourism and recreation sector as an important source of economic revenues in the area.

    e. Landscape aesthetics: Relevant as the non-tangible benefits enhancing the well-being of local citizens, visitor and tourists.

The assessment of all selected ES was conducted at the spatial resolution of 100 m x 100 m (1 ha), using multiple spatial explicit modelling approaches based on the type of the ES assessed (described in detail below). In general, while the assessment of provisioning services was conducted as a simple pilot analysis of proxy data, cultural services were assessed using static spatially explicit modelling approaches; the assessment of hydropower production and all regulating services was conducted using the InVEST suite of spatially explicit biophysical models.

The main data sources for all modules of the InVEST are LULC maps, supplemented by various environmental and socio-economic parameters (Table 7). A detailed description of the modelling assumptions, processes and limitations is provided in (Kareiva et al., 2011) and (Sharp et al., 2015); therefore, they are not fully reproduced but rather outlined for an easier orientation in the modelling processes in this study.

To assess hydropower production and regulating services in this study, we utilized InVEST model versions 2.4.4 and 3.1.3.

Table 7. Data inputs into the InVEST modules utilized.

Data inputs	Data source
All modules	
Current LULC (baseline)	CORINE Land Cover 2006 (EEA, 2007)
Future LULC (LULC scenarios)	Participative LULC scenarios to 2050
Hydropower production, Water quality regulation: nitrogen retention	
Elevation	ZABAGED Contours (ČÚZK, 2013)
Soil depth	SOWAC-GIS Geoportal (VÚMOP, 2014)
Plant available water content	
Average annual precipitation	Climate projections based on RCP4.5 and RCP8.5 emission scenarios (results of future climate modelling with the Aladin-CLIMATE/CZ model for the area of the Czech Republic; Global Change Research Institute CAS, v.v.i.) (Štěpánek et al., 2009, 2011)
Average annual potential evapotranspiration	
Evapotranspiration coefficients	(Sharp et al., 2015)
Watersheds and subwatersheds	DIBAVOD hydrological database (VÚV TGM, 2014)
Root depth	(Canadell et al., 1996; Sharp et al., 2015)
Water demand by different LULC types	(Sharp et al., 2015), stakeholder consultations
Nitrogen export coefficients	(Reckhow et al., 1980; Sharp et al., 2015)
Vegetation filtering efficiency	(Sharp et al., 2015)
Climate regulation	
Carbon pools for different LULC types (aboveground, belowground, soil, dead organic matter)	Literature review (Smith et al., 1997; Joyce, 2001; IPCC, 2003, 2006; Mund, 2004; Green et al., 2007; Cienciala et al., 2008; Schumacher and Roscher, 2009; Lindsay, 2010;

	IFER, 2010; Janous et al., 2010; Truus, 2011; FOREST EUROPE et al., 2011; CHMI, 2012; De Simon et al., 2012; O'Halloran et al., 2013)
Water quality regulation: sediment retention	
Elevation	ZABAGED Contours (ČÚZK, 2013)
Soil erodibility index (K)	SOWAC-GIS Geoportal (VÚMOP, 2014)
Rainfall erosivity index (R)	(Dostál et al., 2006; Janeček and et al., 2012)
Watersheds and subwatersheds	DIBAVOD hydrological database (VÚV TGM, 2014)
Vegetation filtering efficiency	(Sharp et al., 2015)

2.5.1 Provisioning services

2.5.1.1 Crop production

To assess crop production, we applied a simple statistical approach based on proxy data, introduced by multiple studies worldwide (Raudsepp-Hearne et al., 2010; Queiroz et al., 2015). This approach assesses potential crop production based on the extent of agricultural land in different scenarios. In this study, crop production was assessed based on the aggregate area of Non-irrigated arable land present in the baseline landscape in 2006 and in different LULC change scenarios in 2050.

This rather simple method was decided not to be combined with predictions of agricultural productivity under different climate change scenarios, since the available predictions of agricultural production are burdened by a significant level of uncertainties (Rounsevell et al., 2005). Therefore, we decided to limit this additional source of uncertainty and to rely solely on LULC data.

2.5.1.2 Timber production

Similarly to crop production, timber production was assessed based on proxy data, in this case the proportion of Broad-leaved forest, Coniferous forest and Mixed forest land present in the study areas in the baseline landscape (2006) and the scenarios to 2050 (Raudsepp-Hearne et al., 2010; Queiroz et al., 2015). Similarly to the case of crop production, it was decided not to introduce additional source of uncertainty by incorporating projections of future forest productivity under different climate change projections.

2.5.1.3 Hydropower production

Potential contribution of ecosystems to hydropower production was modelled with the corresponding InVEST module based on water yield provided by the study landscape, contributing to the operation of a local hydropower plant at the Lipno reservoir. Conceptually, the contribution to hydropower production is calculated as:

$$HP = f(W_y) \quad (6)$$

where HP represents hydropower production in kWh per year as a function of average annual water yield from the reservoir watershed within the study area (W_y). Average annual water yield is calculated as the difference between average annual precipitation (P), evapotranspiration (E), water retention by ecosystems (W_r) and water consumption (W_c) by different LULC types:

$$W_y = P - E - W_r - W_c \quad (7)$$

In the calculation of water retention by ecosystems (W_r), vegetation type and soil parameters are taken into account.

The main data inputs for the analysis (Table 7) were derived from national sources, comprising digital elevation model, soil parameters (soil depth, plant available water content), and watershed and sub-watershed boundaries. Climate parameters, namely average annual precipitation and evapotranspiration for the baseline year (2006) and scenarios to 2050 were derived from RCP-based climate projections provided by Global Change Research Institute CAS (Table 5, Table 6).

The contribution of ecosystems to hydropower production was not quantified for the entire area of the case study sites, but only for the watersheds contributing to local water reservoirs with hydro-power plants (the Lipno water reservoir in the case of Šumava BR). The results were aggregated to the sub-watershed level as recommended by (Sharp et al., 2015), since the modelling outputs rendered on the scale of grid-cells are not suitable for direct interpretation.

2.5.2 Regulating services

2.5.2.1 Climate regulation

The ecosystem service of climate regulation was assessed in terms of the change in carbon stocks between the baseline landscape in 2006 and the scenarios in 2050. In this study, we define climate regulation in line with (Sharp et al., 2015) as the sum of carbon stored in the landscape at a certain time, which conveys the capacity of the landscape to regulate the amount of greenhouse gases in Earth's atmosphere.

Besides LULC datasets (for the baseline landscape and the scenarios), the input parameters of the model comprise the amount of carbon stored in four carbon pools (aboveground biomass, belowground biomass, soil carbon and dead organic matter) for each LULC category (Table 7, Table 8). This data was compiled from a review of studies originating from areas with similar geographic and climatic conditions as the study areas, together with IPCC reports (Table 7). The relative root-to-shoot ratio for trees was estimated at 0.2 and the fraction of carbon in biomass was set at 50%, in accordance with Czech inventories under the UNFCCC (CHMI, 2012).

In terms of the modelling process, the model sums the amount of carbon stored in each raster cell in the baseline landscape and future scenarios and calculates the difference, which conveys the change in climate regulation capacity reached under a certain scenario (equations (8) –(11)) (Conte, Nelson, et al., 2011).

$$C_{xt} = \sum_{j=1}^{J} A_{xjt} \ (C_{aj} + C_{bj} + C_{sj} + C_{dj}) \quad (8)$$

In the first step, the amount of carbon stored in site x at time t is calculated (C_{xt}). For each LULC type j ($j \in \langle 1; J \rangle$), A_{xjt} presents the area of j in site x at time t, while C_{aj}, C_{bj}, C_{sj} and C_{dj} represent metric tonnes of carbon stored per hectare (tC ha^{-1}) in the aboveground, belowground, soil and dead organic matter pools.

To determine the aggregate amount of carbon stored across the landscape at time t (C_t), the site-level carbon storage values (C_{xt}) are summed across all sites x ($x \in \langle 1; X \rangle$):

$$C_t = \sum_{x=1}^{X} C_{xt} \quad (9)$$

To determine the change in carbon stocks in site x in a period from year t to year T ($t < T$), carbon stored in $C_{xt'}$ is subtracted from $C_{xT'}$:

$$\Delta C_{xtT} = C_{xT'} - C_{xt'} \quad (10)$$

Finally, ΔC_{tT} gives the change in carbon stocks in period from t to T over the entire landscape:

$$\Delta C_{tT} = \sum_{x=1}^{X} \Delta C_{xtT} \tag{11}$$

Climate regulation was calculated for the whole study area and the results are presented in the original resolution 100 m x 100 m.

Table 8. Carbon pools in different land use and land cover categories (input for the climate regulation InVEST model) [t C ha^{-1}]

LULC type	Aboveground	Belowground	Soil	Dead organic matter
Discontinuous urban fabric	2	1	5	0
Industrial or commercial units	0	0	0	0
Road and rail networks and associated land	0	0	0	0
Mineral extraction sites	0	0	0	0
Green urban areas	113	23	70	1
Sport and leisure facilities	0	0	0	0
Non-irrigated arable land	5	2	59	0
Fruit trees and berry plantations	20	5	40	1
Pastures	4	3	69	1
Complex cultivation patterns	8	5	66	1
Land principally occupied by agriculture	5	2	59	0
Broad-leaved forest	113	23	70	10
Coniferous forest	92	18	70	13
Mixed forest	96	19	70	13
Natural grasslands	10	3	75	1
Transitional woodland-shrub	8	8	70	3
Inland marshes	3	6	87	2
Peat bogs	5	7	100	2
Water bodies	0	0	0	0

2.5.2.2 Water quality: Nitrogen

In this study, we focused on two aspects of the ecosystem service of water quality regulation, specifically on nitrogen and sediment retention. In accord with the conceptualization of ES provision by (Villamagna et al., 2013), who introduces the concepts of ES provision capacity, flow, demand and pressure, we modelled three aspects of water quality regulation:

$$\Delta E = D - R \tag{12}$$

where D represents the amount of pollutants discharged (nitrogen and eroded soil, respectively), indicating what pressure each scenario imposes on local environmental conditions. R represents the amount of pollutants retained in the landscape as a measure of the capacity to provide an ecosystem service, and ΔE the amount of pollutant exported annually to the stream network. ΔE served as the basis for the final analysis of trade-offs between ES.

To assess the impact of various scenarios on pollutant discharge, retention and export, we used the InVEST model. In the modelling process, first, the amount of pollutants discharged from each raster cell of the study area is quantified. Subsequently, the retention of pollutants and their final export to water courses is calculated. The model calculations are performed on a grid-cell scale; however, we present the results aggregated for subwatersheds, as the outputs of the utilized InVEST modules are not supposed to be interpreted on the grid-cell level (Sharp et al., 2015).

The modelling process consists of three steps. In the first step, the annual water yield from each watershed is calculated. In the second step, the amount of nitrogen discharged from each watershed and the proportion retained by ecosystems is quantified. Finally, the amount of pollutant exported to water courses is calculated.

The modelling process is described by following equations (Tallis et al., 2011). First, the annual water yield (Y_{jx}) is assessed for each pixel of the landscape (x) with certain LULC type (j):

$$Y_{jx} = P_x - AET_{jx} \tag{13}$$

where AET_{jx} is the annual actual evapotranspiration on pixel x with LULC j and P_x is the annual precipitation of pixel x.

For each pixel, nitrogen discharge is quantified based on export coefficients distinctive for each LULC type, which are adjusted to local conditions:

$$ALV_x = HSS_x \cdot pol_x \tag{14}$$

where ALV_x is the adjusted loading value at pixel x, HSS_x the hydrologic sensitivity score at pixel x and pol_x the export coefficient.

The hydrologic sensitivity score is calculated as:

$$HSS_x = \frac{\lambda_x}{\bar{\lambda}_W} \tag{15}$$

$$\lambda_x = \log\left(\sum_U Y_u\right) \tag{16}$$

where λ_x is the runoff index at pixel x (calculated as follows) and $\bar{\lambda}_W$ is the mean runoff index in the watershed of interest. $\sum_U Y_u$ represents the sum of the water yield of pixels along the flow path above pixel x.

Subsequently, the model routes down the water runoff path, determined by slope, carrying the nitrogen discharged and allows each pixel downstream from polluting pixel to retain nitrogen based on its land cover type and corresponding ability to retain nitrogen. The resulting proportion of nitrogen retained by each downstream pixel is aggregated for watersheds and subwatersheds.

Finally, the model quantifies what proportion of nitrogen reaches the streams by subtracting the amount of nitrogen retained from the amount of nitrogen discharged in each watershed, resulting in the amount of nitrogen exported to water streams (equation (12)).

The main data inputs into the model are LULC raster datasets, soil properties, slope, and nitrogen export coefficients (Table 7, Table 9). The nitrogen export coefficients were derived from a comprehensive study by (Reckhow et al., 1980), supplemented by additional export coefficients from (Sharp et al., 2015). In the case of water bodies, the nitrogen export coefficient was adopted from a localized study by (IUCN, 1996) (Table 9) and adjusted for each scenario based on its storyline; while the scenarios focusing on nature conservation were assigned lower level of nitrogen discharge from fishponds, the scenarios assuming intensive fisheries industry were assigned higher values. In the area of Třeboň Basin, the nitrogen export coefficient for water bodies exceeded all other coefficients, since the intensively fertilized fishponds represent a major nitrogen input into the landscape (the annual fertilizer input can reach up to 140 kg N ha^{-1}) (IUCN, 1996).

Table 9. Nitrogen export coefficients (input for the nutrient retention model) [g ha^{-1} yr^{-1}]

LULC type	Nitrogen export coefficient		
Discontinuous urban fabric			7.5
Industrial or commercial units			13.8
Road and rail networks and associated land			0.0
Mineral extraction sites			1.0
Green urban areas			4.0
Sport and leisure facilities			8.0
Non-irrigated arable land			11.0
Fruit trees and berry plantations			10.0
Pastures			3.1
Complex cultivation patterns			10.0
Land principally occupied by agriculture			9.0
Broad-leaved forest			1.8
Coniferous forest			1.8
Mixed forest			1.8
Natural grassland			3.1
Transitional woodland-shrub			2.0
Inland marshes			1.0
Peat bogs			1.0
	Scenario		
	Baseline (2006), BaU, Biofuels	Conservation	Exploitation, Markets
Water bodies	10.0	5.0	15.0

2.5.2.3 Water quality: Sediments

Similarly to water quality regulation related to nitrogen retention, we conceptualized sediment retention in accord with (Villamagna et al., 2013) and the InVEST modelling process (Tallis et al., 2011) as consisting of three aspects: sediment discharge (D), retention (R) and export (ΔE) (equation (12)).

To calculate sediment discharge from site x ($USLE_x$), the InVEST module utilizes the Universal Soil Loss Equation (USLE; (Wischmeier and Smith, 1978)), developed to quantify the average annual soil loss resulting from water erosion:

$$USLE_x = R_x \cdot K_x \cdot LS_x \cdot C_x \cdot P_x \qquad (17)$$

where R_x is the rainfall erosivity (the potential of rainfall to move and erode soil, as a function of regionally-specific average precipitation intensity and duration), K_x presents soil erodibility (soil's susceptibility to erosion, as a function of soil characteristics), LS_x characterizes slope length and steepness, C_x presents the crop or vegetation factor and P_x presents the management factor (taking into account specific erosion control practices, such as contour tilling) (Conte, Ennaanay, et al., 2011).

Subsequently, the proportion of sediments retained SR_x at site x, originating from the sites higher upstream (y, z) is calculated as:

$$SR_x = E_x \sum_{y=1}^{x-1} USLE_y \prod_{z=y+1}^{x-1} (1 - E_z) \qquad (18)$$

where E_x stands for the sediment retention efficiency of the LULC type at site x, $USLE_y$ presents sediment discharge from upstream site y and E_z presents the sediment retention efficiency of the LULC type at site z.

The data inputs, such as digital elevation model, soil properties and USLE parameters, were derived primarily from national data sources (Table 7).

The contribution of ecosystems to sediment retention was not quantified for the entire area of the case study sites, but only for the watersheds contributing to local water reservoirs with hydro-power plants (the Lipno water reservoir in the case of Šumava BR and the watersheds related to fishponds in Třeboň Basin BR). Similarly to the previous cases of water-related ES, the results were aggregated to the sub-watershed level as recommended by (Sharp et al., 2015).

2.5.3 Cultural services

In order to keep the coherence with the assessment of provisioning and regulating ES in the previous parts of the study, we approached the assessment of cultural ES from a GIS perspective, focusing on the link between various landscape attributes (such as LULC composition and configuration, presence of certain landscape features or presence of ecologically valuable phenomena) and their potential in terms of recreation and aesthetic quality.

2.5.3.1 Recreation potential

To assess the recreational potential of selected biosphere reserves, we applied a modelling approach developed within the EU initiative on mapping ecosystem services (MAES) to achieve Action 5 of the EU Biodiversity Strategy to 2020 (EC, 2011; Maes et al., 2013, 2015). This approach, denoted as ESTIMAP, is designed for ES mapping and was developed by the European Commission's Joint Research Centre (JRC) (Zulian et al., 2013, 2014). The Recreational potential tool of ESTIMAP was designed as a flexible framework, to be adjusted according to the type of the study landscape and its major assets (Paracchini et al., 2011, 2014).

Within this modelling approach, the supply of the ecosystem service of recreation is understood as the potential of landscape to facilitate outdoor activities and recreation. In general, the model aggregates several partial indicators, conveying the potential of a landscape to provide opportunities for outdoor recreation, into a composite recreation potential index (RPI). RPI is communicated as a normalised range between 0 and 1 (OECD, 2008).

To build the composite index of recreation potential, we followed a study by (Paracchini et al., 2014), which summarizes available findings from studies on outdoor recreation and consumer behaviour, such as preferences of EU residents towards destination type, type of ecosystems, travelled distance, etc. Based on this study, we selected an array of component indicators suitable for the study area, as well as the relative scores assigned to them (where appropriate). Table 10 summarizes all component indicators of RPI employed in this study, together with their interpretation, the categorization of indicator values, their relative scores and respective data sources.

Table 10. Parametrization of the ESTIMAP approach to quantify the Recreation Potential Index (RPI) in the selected study areas.

Outdoor recreation-related phenomenon	Interpretation	Indicator	Indicator category	Indicator score assigned	Source
Degree of naturalness	Measure of human influence on landscape and species	Mean Species Abundance (MSA)	Discontinuous urban fabric	0.10	CLC 2006 (EEA, 2007) and future LULC scenarios built in this study; MSA scores
			Industrial or commercial units	0.05	
			Road and rail networks	0.05	

			Mineral extraction sites	0.05	derived from Vačkář et al. (2016)
			Green urban areas	0.20	
			Sport and leisure facilities	0.20	
			Non-irrigated arable land	0.10	
			Pastures	0.30	
			Complex cultivation patterns	0.20	
			Land principally occupied by agriculture	0.20	
			Broad-leaved forest	0.40	
			Coniferous forest	0.20	
			Mixed forest	0.40	
			Transitional woodland-shrub	0.20	
			Inland marshes	1.00	
			Peat bogs	1.00	
			Water bodies	0.40	
Level of nature protection	Level of protection according to EU directives, national legislation and regulations	Presence of protected areas	Natura 2000 site	0.50	Nature Conservation Agency of the Czech Republic (AOPK ČR)
			National natural monument	0.50	
			National nature reserve	0.50	
			Natural monument	0.50	
			Natural reserve	0.50	
Water proximity	Proximity of rivers for outdoor	Proximity to river bank	0-1 km	1.00	ArcČR 500 3.0 database (ARCDATA,

	recreation		1-2 km	0.70	2012), ArcGIS spatial analysis (ESRI, 2013)
			Beyond 2 km	0.00	
	Proximity of water bodies for outdoor recreation	Proximity to water-body shores	Water bodies	1.00	
			0-1 km	0.80	
			1-2 km	0.50	
			Beyond 2 km	0.00	
Area of ecosystem	An additional measure of ecosystem naturalness; applied only on patches with MSA > 0.1 and area > 0.1 ha	Hectares	Continuous scale	Normalized according to equation (19)	CLC 2006 (EEA, 2007) and future LULC scenarios built in this study
Trail proximity	Proximity of hiking and cycling trails for outdoor recreation	Km of trails per km^2 of municipality cadastral area	Continuous scale	Normalized according to equation (19)	Administrations of Třeboň Basin PLA and BR; Administration of Šumava NP

The modelling framework applied in this analysis is shown in Figure 12. The process of building RPI was based on an aggregation of individual component indicators by a series of summations and normalisations. The normalisation of both the partial indicators and the composite index RPI was calculated as

$$i_{norm} = \frac{i - i_{min}}{i_{max} - i_{min}} \tag{19}$$

where i_{norm} is the normalized value of an indicator, reaching values between 0 and 1, i is the original value of the indicator, i_{min} its minimal and i_{max} its maximal values in the dataset (OECD, 2008).

In addition to the indicator values listed in Table 10, the indicator of lakes' proximity was assigned different weights for different scenarios in Třeboň Basin BR case study. The weights equalled 1 for the Conservation scenario, since this scenario assumed the highest emphasis on non-production functions of water bodies, thus implicitly assuming their higher recreational potential. Following the same reasoning, under the Exploitation scenario this component indicator was assigned a weight of 0, assuming zero level of protection and a full exploitation of water bodies by local fishing industry.

In line with their storylines, the Baseline, BaU and Biofuels scenarios were assigned a weight of 0.8, while the Market scenario received a weight of 0.5.

The data layers for all component indicators as well as subsequent operations were processed using spatial modelling tools available within the ArcGIS platform. All analyses were conducted with raster files of a 100 x 100 m cell resolution.

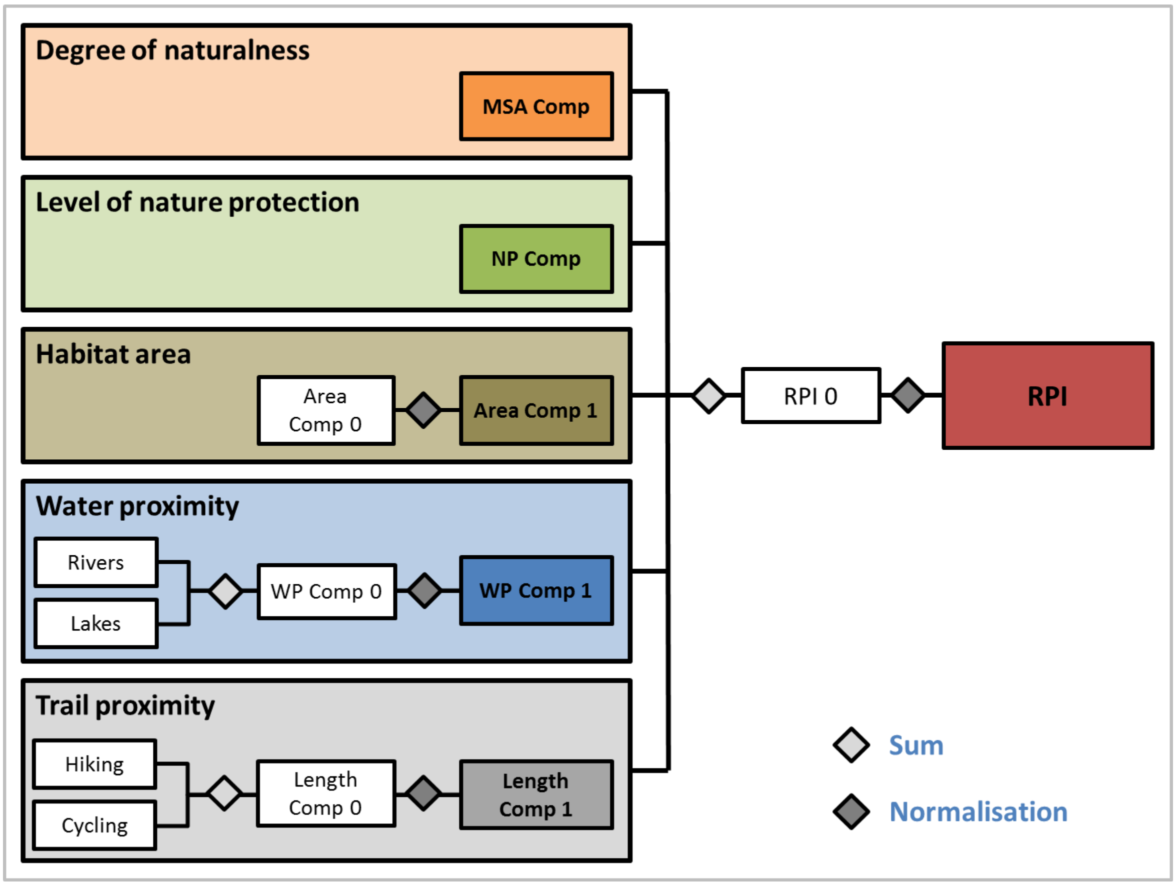


Figure 12. A conceptual framework of the aggregation of component indicators (Comp) into the recreation potential index (RPI) through a series of summations and normalisations.
(Source: According to Paracchini et al., 2014)

2.5.3.2 Landscape aesthetics

Landscape aesthetics were assessed based on physical landscape characteristics, following and adjusting an approach developed by Otero Pastor et al. (2007) and Martín Ramos and Otero Pastor (2012) to assess the aesthetical potential of European landscapes based on perception surveys focusing on the most preferred landscape characteristics and patterns. The method assumes that “a hypothetical observer evaluates landscape quality for each pixel through examining landscape characteristics represented in map overlays" (Martín Ramos and Otero Pastor, 2012), considering the following landscape attributes:

1. Land use and land cover type;
2. Terrain forms;
3. Presence of water;
4. Presence of human activities.

While LULC type, diverse terrain forms and presence of water are considered positive for landscape aesthetics in this approach, the presence of human activities is considered as hampering landscape aesthetics potential.

The aggregate index of landscape aesthetics in grid-cell i (LAI_i) is calculated as:

$$LAI_i = [U_i * A_i * T_i] - H_i \quad (20)$$

where U_i is the LULC value, A_i is the value of water presence, T_i is the value of the land forms and T_i the value of human activity (Martín Ramos and Otero Pastor, 2012).

The value of LULC type was assessed calculating the mode of the cells in a radius of 1 km around each cell, and subsequently assigning each cell a value of U_i according to Table 11.

Table 11. Value of variable U_i for different land use and land cover types (according to Martín Ramos and Otero Pastor, 2012).

LULC type	U_i
Non-irrigated arable land	4
Pastures	5
Complex cultivation patterns	6
Land principally occupied by agriculture	6
Broad-leaved forest	9
Coniferous forest	7
Mixed forest	8
Transitional woodland-shrub	6
Natural grassland	5
Inland marshes	9
Peat bogs	9

The impact of the complexity of the relief forms on visual landscape quality was adapted from (Otero Pastor et al., 2007), assigning the variable T_i a value based on the slope steepness (Table 12).

Table 12. Value of variable T_i for different levels of slope steepness (according to Otero Pastor et al., 2007).

T_i	Slope steepness [%]	
	min	max
9.4	0	3
9.7	3	5
9.8	5	7
9.9	7	9
10.0	9	11
10.1	11	13
10.1	13	15
10.2	15	20
10.3	20	25
10.6	25	65

The presence of water was evaluated in pixels within a specified distance from water bodies, while pixels closer to water bodies were assigned a value greater than more distant pixels. The values of A_i were assigned according to:

$$A_i = a + b \sum \frac{1}{d_K^2} \quad (21)$$

where a and b are coefficients whose value is adjusted considering that A_i has a value of 1.5 in the pixel nearest to water and value 1 at a distance of 1 km (Martín Ramos and Otero Pastor, 2012), and d_K is the distance from grid-cell i to water bodies.

The proximity of human activities, considered as a negative feature in terms of landscape aesthetics, was calculated as:

$$H_i = I_i + M_i \quad (22)$$

where I_i indicates the presence of industry and M_i the presence of mining activities.

In accord with (Martín Ramos and Otero Pastor, 2012), each grid-cell was assigned a value based on its proximity to industrial and mining sites, the higher the value, the more negative impact on landscape aesthetics. Similarly to water presence, the variable H_i was calculated as:

$$H_i = a + b \sum \frac{1}{d_K^2} \quad \textbf{(23)}$$

where a and b are coefficients whose value is adjusted considering that H_i in the grid-cell nearest the presence of human activities takes value 14 in the case of industrial sites and 7 in the case of mining sites. In the grid-cells located at a distance above 1 km, the value of H_i is 0 (Martín Ramos and Otero Pastor, 2012); d_K is the distance from grid-cell i to industrial sites and mining sites, respectively.

The resulting values of LAI for each scenario were normalized according to equation (19).

The data inputs into the analysis were CORINE Land Cover 2006 datasets (EEA, 2007) and the future LULC scenarios built in this study, combined with the location of water bodies derived from ArcČR 500 3.0 database (ARCDATA, 2012) and a digital elevation model based on ZABAGED Contours (ČÚZK, 2013).

Similarly to the analysis of recreation potential, the data layers for all component indicators as well as subsequent operations were processed using spatial modelling tools available within the ArcGIS platform. All analyses were conducted with raster files of a 100 x 100 m cell resolution.

2.6 Ecosystem service trade-offs

The final step of the analysis conducted in this study was the assessment of ES trade-offs, building on the assessment of provision of different types of ES for multiple future scenarios in the previous steps.

The trade-offs between different types of ES were assessed through relative change between the provision of each ES in the baseline landscape (2006) and a scenario to 2050 (ΔES, in per cent):

$$\Delta ES = \left(\frac{ES_t}{ES_\tau} - 1\right) * 100 \quad \textbf{(24)}$$

where ES_τ is the provision of a given ES in respective units in time $\tau = 2050$, while ES_t presents the provision of the service in time $t = 2006$.

In order to facilitate a relative comparison of trade-offs between different scenarios, the change in the provision of each ecosystem services x (ΔES_x) was recalculated to gain its relative magnitude in comparison with a 1% change in a selected type of ES, in this case climate regulation. In other words, this approach shows how many per cent increase or decrease a selected ES encountered while climate regulation changed by 1%:

$$T_x = \frac{\Delta ES_x}{\Delta ES_{CR}} \tag{25}$$

where T is the relative level of the change in the provision of ecosystem service x and ΔES_{CR} in the change in provision of climate regulation between the baseline and a given scenario.

This approach has been established by studies focusing on ES trade-offs, since it facilitates easier illustration of the relative relationships within and between bundles of ES in the cases when other means of comparison, such as in currency units, are not applicable (Nelson et al., 2010).

Numerous studies (e.g. conducted within the TEEB initiative (TEEB, 2010)) have analysed trade-offs between ES by comparing their economic value in monetary terms. However, economic evaluation of ES was outside the scope of this study, which aimed to assess ES in biophysical terms. Therefore, while not being able to use monetary units as a means of comparing the provision of different ES, we applied the relative score to a unit change in carbon to facilitate the trade-off analysis.

2.7 Data requirements and sources

For easier orientation in the modelling process, this section (Table 13) summarizes the above described data required for the analyses and the data sources utilized in this thesis.

Table 13. Summary of data requirements and sources used in the study

Data requirement	Data source
LULC change scenarios	
Current LULC	CORINE Land Cover 2006 (EEA, 2007)
Future LULC	ALARM 2050 scenarios (Rounsevell et al., 2006; Spangenberg, 2007; Spangenberg et al., 2012)
Participatory input from stakeholders	Storylines from participative scenario building workshops in the case study areas
Ecosystem services assessment	
All services	
Current LULC	CORINE Land Cover 2006 (EEA, 2007)
Future LULC	CLC 2006 and participative LULC scenarios to 2050 developed in the previous step
Crop production, Timber production	
No additional data to LULC dataset required	
Climate regulation	
Carbon pools for different LULC types (aboveground, belowground, soil, dead organic matter)	Literature review (Smith et al., 1997; Joyce, 2001; IPCC, 2003, 2006; Mund, 2004; Green et al., 2007; Cienciala et al., 2008; Schumacher and Roscher, 2009; Lindsay, 2010; IFER, 2010; Janous et al., 2010; Truus, 2011; FOREST EUROPE et al., 2011; CHMI, 2012; De Simon et al., 2012; O'Halloran et al., 2013) Final values of carbon pools are summarized in Table 8.
Hydropower production, Water quality regulation: nitrogen retention	
Elevation	ZABAGED Contours (ČÚZK, 2013)
Soil depth	SOWAC-GIS Geoportal (VÚMOP, 2014)
Plant available water content	
Average annual precipitation	Climate projections based on RCP4.5 and RCP8.5 emission scenarios (results of future climate modelling with the Aladin-CLIMATE/CZ model for the area of the Czech Republic; Global Change Research Institute CAS, v.v.i.) (Štěpánek et al., 2009, 2011)
Average annual potential evapotranspiration	
Evapotranspiration coefficients	(Sharp et al., 2015)
Watersheds and subwatersheds	DIBAVOD hydrological database (VÚV TGM, 2014)
Root depth	(Canadell et al., 1996; Sharp et al., 2015)
Water demand by different LULC types	(Sharp et al., 2015), stakeholder consultations
Nitrogen export coefficients	(Reckhow et al., 1980; Sharp et al., 2015) Final values of carbon pools are summarized in Table 9.
Vegetation filtering efficiency	(Sharp et al., 2015)

Water quality regulation: sediment retention	
Elevation	ZABAGED Contours (ČÚZK, 2013)
Soil erodibility index (K)	SOWAC-GIS Geoportal (VÚMOP, 2014)
Rainfall erosivity index (R)	(Dostál et al., 2006; Janeček and et al., 2012)
Watersheds and subwatersheds	DIBAVOD hydrological database (VÚV TGM, 2014)
Vegetation filtering efficiency	(Sharp et al., 2015)
Recreation potential	
Degree of naturalness	Mean Species Abundance (MSA) indicator scores for different LULC types were derived from Vačkář et al. (2016) and calculated for CLC 2006 and participative LULC scenarios to 2050
Level of nature protection	Nature Conservation Agency of the Czech Republic (AOPK ČR)
Water proximity	ArcČR 500 3.0 database (ARCDATA, 2012)
Area of ecosystem	CLC 2006 and participative LULC scenarios to 2050
Trail proximity	Administrations of Třeboň Basin PLA and BR; Administration of Šumava NP
Landscape aesthetics	
Terrain forms	ZABAGED Contours (ČÚZK, 2013)
Presence of water	ArcČR 500 3.0 database (ARCDATA, 2012), CLC 2006 and participative LULC scenarios to 2050
Presence of human activities	CLC 2006 and participative LULC scenarios to 2050
Trade-off analysis	
Level of provision of various types of ES	Datasets of ES provision developed in the previous steps.

3 Results

3.1 Scenario storylines

3.1.1 Třeboň Basin Biosphere Reserve

The scenario storylines for Třeboň Basin BR were developed through a series of semi-structured interviews and discussions with local stakeholders, whose influence on the future development of the study area is substantial. Based on the discussions, an array of opinions and preferences regarding potential future development of the area was assembled.

Naturally, the stakeholders focussed mainly on local landscape issues and local driving forces, influencing potential future development of the landscape. Thus, the storylines developed by the stakeholders were considered as storylines acknowledging predominantly the influence of local driving forces (Figure 13).

After compiling a representative sample of stakeholder opinions, we identified a pattern differentiating the evidence from the stakeholders along a gradient of "environmental focus". Evidently, the preferences of stakeholders clustered in two groups, aiming at stronger levels of nature protection and, on the contrary, at stronger use of natural assets provided by the study area. Thus, these groups were compiled into two individual storylines, denoted as Conservation and Exploitation (Figure 13). Furthermore, a Business as Usual (BaU) storyline was identified as a status-quo option, which would to a large extent preserve the current state of the landscape.

To provide a counterbalance to the localized scenario storylines introduced above, we supplemented the scenario storyline matrix by two other storylines, acknowledging the influence of national to global driving forces, such as national and European economic and demographic development, policies, etc. At the same time, we aimed to preserve the pattern of different levels of environmental focus of the storylines, similarly as in the case of localized storylines. Hence, we introduced two additional storylines reflecting the influence of national to global driving forces, denoted as Market and Biofuels (Figure 13).

		Dominant driving forces	
		Global	Local
Strength of environmental focus	High	Biofuels	Conservation
		Business as Usual (BaU)	
	Low	Market	Exploitation

Figure 13. A matrix of the final scenario storylines designed for Třeboň Basin BR.
(Source: Author's elaboration)

The detailed characteristics of the storylines were as follows:

1. **Conservation scenario storyline**. This storyline described a situation when the landscape is fully protected, no intensification of human activities is present, and only transformations to more natural ecosystems (e.g. from arable lands to pastures, from shrub land to forests) are allowed. Examples of the Conservation scenario storyline are restorations of mining sites after the cease of mining due to strict nature conservation, and potential abandonment of intensive agriculture in areas close to nature reserves. This scenario is in line with ALARM BAMBU 2050 scenario storyline.

2. **Business as Usual (BaU) scenario storyline**. Under this storyline, the LULC in Třeboň Basin BR undergoes only minor changes, reflecting current trends and predominantly preserving the landscape in its current state. Landscape changes occurring under this storyline are e.g. moderate growth of urban areas, limited abandonment of agricultural land and increase in forested areas, with the exception of changes affecting strictly protected areas, such as peat bogs and wetlands. This scenario is in line with ALARM BAMBU 2050 scenario storyline.

3. **Exploitation scenario storyline**. The exploitation scenario storyline depicted a situation which would occur if the landscape protection in the study site ceased and the intensification of agriculture and mining, demanded by miners and biogas producers, was permitted. Under this scenario, more pronounced exploitative changes (e.g. extensive increase in mining areas, transformation of pastures into arable land) are projected in the landscape, due to increasing demand for mineral

resources and biomass for bio-gas production in Třeboň. This scenario is in line with ALARM BAMBU 2050 scenario storyline.

4. **Biofuels scenario storyline**. This storylines reflects the European-scale driving forces, namely policies promoting the operationalization of sustainable development targets, such as halted biodiversity loss, competitive economy and healthy environment, gender equity and international cooperation. An important characteristic of this scenario is a substantial increase in the production and use of biofuels. This scenario is in line with ALARM SEDG 2050 scenario storyline.

5. **Market scenario storyline**. This storyline neglects the European-scale driving forces, namely further liberalization and globalization of the market. It assumes higher deregulation of trade, with economic growth presenting a key target. Under this scenario, environmental policies focus mainly on retroactive actions and measures for biodiversity protection are limited. This scenario is in line with ALARM GRAS 2050 scenario storyline.

As emphasized for each storyline, while the first three storylines assume predominance of local driving forces and only moderate changes in national to global driving forces, the last two storylines focus mainly on the European-wide development. Therefore, the Conservation, BaU and Exploitation storylines were further processed based on ALARM BAMBU 2050 scenario, while the Biofuels and Market storylines were further analysed based on ALARM SEDG 2050 and ALARM GRAS 2050 scenarios.

3.1.2 Šumava Biosphere Reserve

The scenario storylines for Šumava BR were developed through a series of participative exercises during scenario-building workshops with local stakeholders.

In this case, during an initial plenary discussion, the majority of the stakeholders agreed on two opposite storylines, denoted as the Green storyline, prioritizing continued nature conservation and implementation of climate change adaptation measures, and the Red storyline, promoting intensive economic development of the area without climate change adaptation. The main reason for this distinction of two storylines along the gradient of the strength of environmental focus was that the current discussion about the future of Šumava region mainly addresses these two extremes; therefore, these two scenario storylines accurately described two contrasting ways of development, which are likely to be pursued in the near future (Figure 14).

The second gradient of storylines considered was the aspect of potential adaptation to future climate change, influencing local ecosystems and the provision of ES (Figure 14).

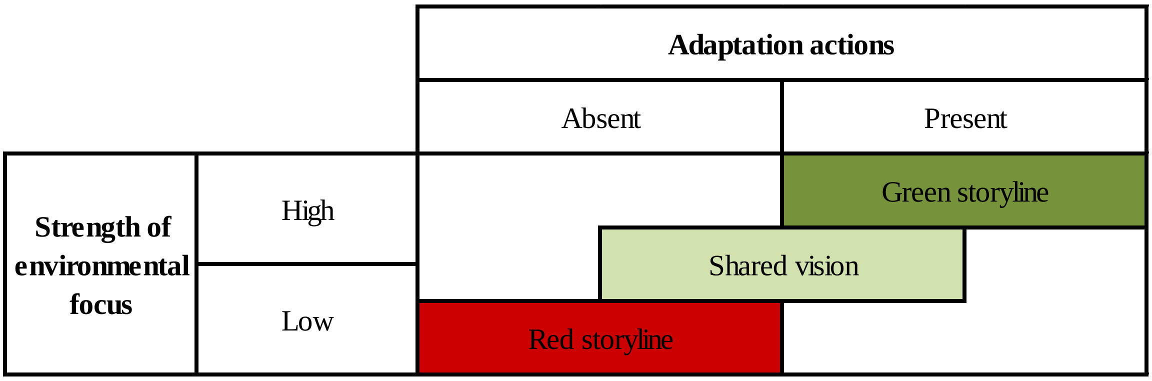


Figure 14. A matrix of the final scenario storylines designed for Šumava BR.
(Source: Author's elaboration)

Afterwards, during following sub-group exercises, the participants created a number of alternative partial visions. Although the stakeholders were not instructed to try to reach a consensus on a single vision, the opinions resulting from sub-group discussions were very similar and after revising some minor differences in the follow-up discussions, the participants created a 'Shared vision' for the future of the study area.

Thus, as a part of the storylines developed, the stakeholders identified adaptation measures suitable for the study area, from the perspective of their expertise. Since large-scale construction of technological measures is restricted in the area, the participants focused mainly on ecosystem-based (EbA) climate change adaptation measures, enhancing the resilience of local ecosystems against potential impacts of climate change (e.g. sustainable forest management and forest conservation). All proposed adaptation measures complied with differentiated conservation regimes in various zones of the NP and the PLA, assuming less intensive activities in the Zones I and II and, on the contrary, targeting the adaptation measures to the peripheral zones of the study area.

The detailed characteristics of the storylines were as follows:

1. **Red storyline: Development without adaptation**. The Red storyline assumed an emphasis on economic development in the study area, without an emphasis on its sustainable dimension. The main driving forces in this storyline were population growth, construction of citizen and touristic infrastructure (e.g. tourist centres apartments) and an intensive touristic and recreational use of the area. In this storyline, various development plans such as designation of new ski slopes, ski lifts and paved hiking trails were proposed. Furthermore, the construction of several small-scale artificial water reservoirs was proposed in order to meet the growing water demands. The area of the NPs Zone I was proposed to decrease, while logging would become more intensive in some of the peripheral forested areas of Šumava. Since no part of the study area would be left to a non-intervention regime, this storyline incurred increasing forest management costs. The proportion of urbanized and other intensively used areas increased. This storyline assumed that climate change will not be perceived as a serious threat; therefore, no adaptation measures will be implemented.

2. **Green storyline: Conservation with adaptation**. The Green storyline assumed that the demographic development in the study area will be stable and the tourism sector will become long-term sustainability oriented. In comparison with the Red storyline, the investments will enhance the quality of local small-scale accommodation capacities, and will not aim to create new large-scale tourist infrastructure. Therefore, this storyline assumed no growth of urbanized areas outside existing tourist resorts. Zone I of the NP was assumed to be enlarged and united, while all current non-intervention zones will be maintained. In this storyline, substantial emphasis was put on potential impacts of climate change, leading to the implementation of adaptation measures, e.g. restoration of degraded forest areas in the peripheral parts of the NP and complete integration of Zone I. The adaptation measures applied in this storyline were primarily ecosystem-based.

   The adaptation measures proposed for the Green storyline included an enlargement and unification of the NP's Zone I as the primary goal. The unified Zone I would be subject to non-intervention management, leading to an increase in forested area. In the peripheral zones of the study area, revitalization of disturbed ecosystems, sustainable forest management and restoration of forests were proposed as suitable adaptation measures. Specifically, the stakeholders proposed using a variety of genotypes in the forest nursery stock, promoting diverse age classes, species mixes, and a variety of successional stages, and introducing spatially complex and heterogeneous vegetation structure. The Green storyline also proposed large-scale peat-bog and marshlands restoration projects.

3. **Shared vision**. The Shared vision favoured a moderate population growth and opposed implementing incentives to increase local population levels, which would not respect local social environment and traditional lifestyle, such as large-scale tourist facilities. In terms of tourism development, the vision preferred investments in qualitative, not quantitative improvements, with emphasized low-impact and sustainable forms of tourism, evenly spread throughout the study area. The vision acknowledged the role of the NP in the area and preferred a partial integration of Zone I forest patches and sustainable forestry and agricultural use of peripheral parts. The need for climate change adaptation was recognized within this storyline and the participants preferred EbA measures

   For the Shared vision, the stakeholders emphasized the threat of water shortages for the future. Therefore, reforestation in the peripheral zones of Šumava together with restoration of peat-bogs were identified as the most favourable solutions to avoid water shortages. Furthermore, this storyline included implementing soft adaptation measures related to water issues such as reduced water use and construction of more efficient water treatment plants. At the same time, the need for differentiated management and adaptation approaches in the Zone I and the peripheral zones of the NP was stressed.

Since all of these storylines presumed the predominance of local to national driving forces, without sharp changes in global drivers, further processing of these storylines was based on ALARM BAMBU 2050 scenario storyline.

3.2 Land use and land cover change scenarios

3.2.1 Třeboň Basin Biosphere Reserve

Figure 15 presents the spatial pattern of LULC change in Třeboň Basin BR in 2050 for five different LULC scenarios. The LULC proportions under in the baseline landscape (2006) and each of the scenarios is provided in Table 14. The aggregate proportion of land undergoing LULC change between 2006 and 2050 in Třeboň Basin BR is 8% for the Market scenario, 21% for the Exploitation scenario, 5% for the BaU scenario, 7% for the Conservation scenario and 17% for the Biofuels scenario.

The results indicate that under all five LULC scenarios, there is an increasing trend in urban areas and a decreasing trend in pastures (Figure 16). The Exploitation scenario comprises the highest increase in intensive LULC types such as industrial and mining sites, as well as a substantial increase in arable land. The Conservation scenario is characterized by a decreasing proportion of mining sites and increase in less human-influenced LULC types, such as forests and pastures. Interestingly, the Market scenario comprises a substantial increase in forest land, while the proportions of pastures and arable land decrease, mainly as a result of European-scale policies and market trends, which are projected to cause agricultural decline and the replacement of agricultural land by forests. The Biofuels scenario is mostly characterized by a vast increase in arable land devoted to the production of biofuels. While the area of natural LULC types (forests, marshes and peat bogs) increased by 5.2% under the Protection scenario, it decreased by almost twice as much (by 9.5 %) under the Exploitation scenario. The smallest change in the proportion of different LULC categories, mainly built-up areas, forests and pastures, occurred under the BaU scenario, since the scenario supposed a limited influence of both local and global driving forces.

The most abundant types of LULC changes in terms of the areal extent occurred between aggregate categories of forests, arable land and grasslands. The most abundant under all scenarios were transitions from grasslands to either forests or arable land. The Biofuels and the Exploitation scenarios were further characterized by the transformation of forests to arable land. Conversely, a change from arable to forest occurred mainly under the Market and the Conservation scenarios.

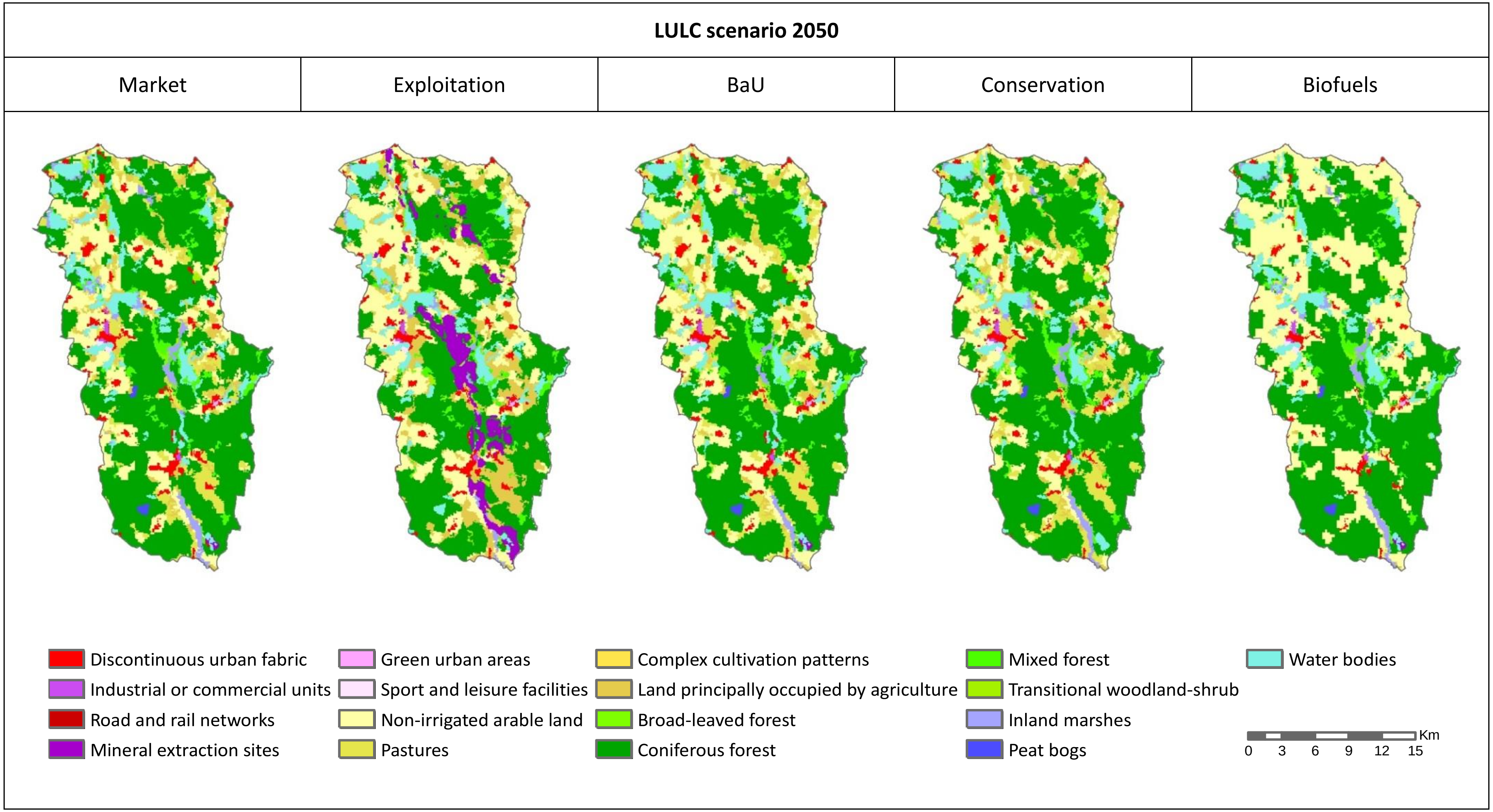
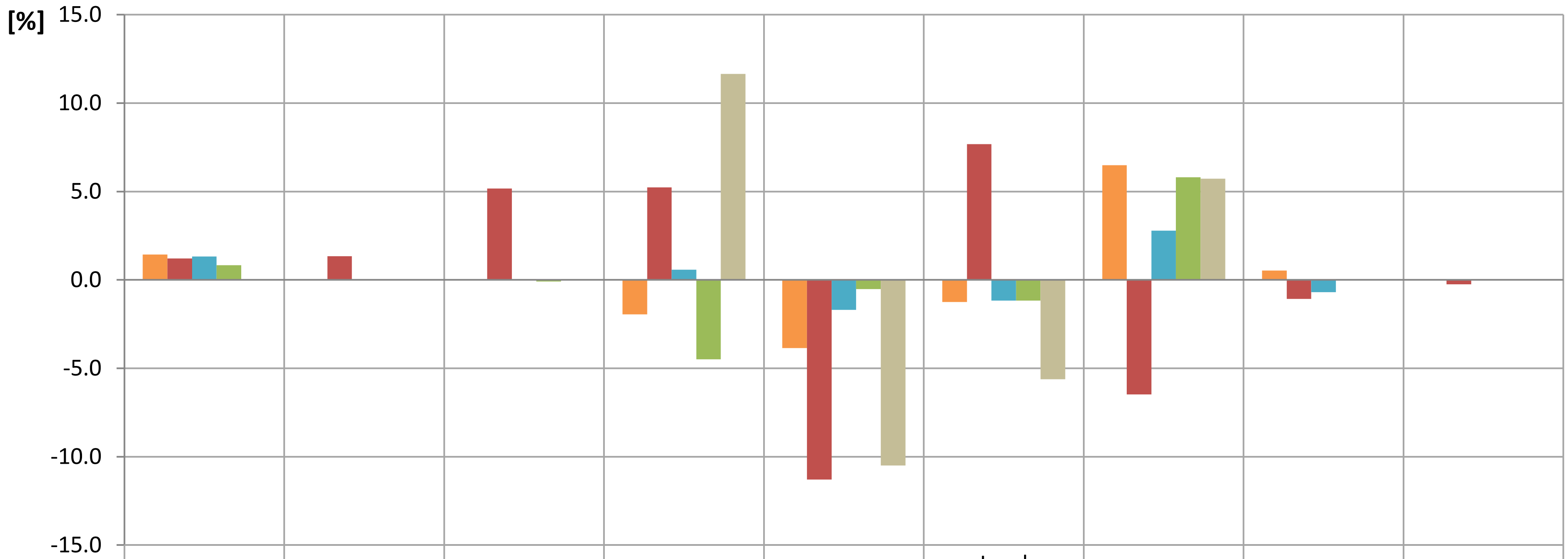


Figure 15. Land use and land cover change scenarios for Třeboň Basins BR in 2050, corresponding to stakeholder storylines.
(Source: Author's elaboration)

Table 14. Proportions of land use and land cover types in Třeboň Basin BR in the baseline year (2006) and in five scenarios to 2050. The total area of Třeboň Basin BR is approximately 70,000 ha.

	Area											
	Baseline (2006)		Market		Exploitation		BaU		Conservation		Biofuels	
	[ha]	[%]	[ha]	[%]	[ha]	[%]	[ha]	[%]	[ha]	[%]	[ha]	[%]
Discontinuous urban fabric	1,531	2.2	2,516	3.7	2,368	3.4	2,441	3.6	2,098	3.1	1,531	2.2
Industrial or commercial units	146	0.2	146	0.2	146	0.2	146	0.2	146	0.2	146	0.2
Road and rail networks	1	0.0	1	0.0	1	0.0	1	0.0	1	0.0	1	0.0
Mineral extraction sites	66	0.1	66	0.1	4,536	6.6	66	0.1	0	0.0	66	0.1
Green urban areas	33	0.0	33	0.0	33	0.0	33	0.0	33	0.0	33	0.0
Sport and leisure facilities	73	0.1	73	0.1	72	0.1	73	0.1	73	0.1	73	0.1
Non-irrigated arable land	13,446	19.6	12,108	17.6	17,040	24.8	13,842	20.1	10,362	15.1	21,456	31.2
Pastures	7,763	11.3	5,109	7.4	0	0.0	6,598	9.6	7,409	10.8	548	0.8
Complex cultivation patterns	36	0.1	29	0.0	36	0.1	30	0.0	30	0.0	36	0.1
Land principally occupied by agriculture	4,318	6.3	3,458	5.0	9,599	14.0	3,515	5.1	3,515	5.1	455	0.7
Broad-leaved forest	452	0.7	330	0.5	234	0.3	359	0.5	452	0.7	389	0.6
Coniferous forest	31,175	45.3	35,633	51.8	26,726	38.9	33,087	48.1	35,159	51.1	35,107	51.1
Mixed forest	2,192	3.2	1,796	2.6	1,523	2.2	1,839	2.7	2,191	3.2	1,912	2.8
Transitional woodland-shrub	610	0.9	179	0.3	339	0.5	176	0.3	195	0.3	88	0.1
Inland marshes	1,299	1.9	1,663	2.4	559	0.8	822	1.2	1,298	1.9	1,299	1.9
Peat bogs	176	0.3	176	0.3	0	0.0	176	0.3	176	0.3	176	0.3
Water bodies	5,427	7.9	5,425	7.9	5,299	7.7	5,420	7.9	5,486	8.0	5,425	7.9



	Discontinuous urban fabric	Industrial or commercial units	Mineral extraction sites	Non-irrigated arable land	Pastures	Land principally occupied by agriculture	Coniferous forest	Inland marshes	Peat bogs
Markets	1.4	0.0	0.0	-1.9	-3.9	-1.3	6.5	0.5	0.0
Exploitation	1.2	1.3	5.2	5.2	-11.3	7.7	-6.5	-1.1	-0.3
BaU	1.3	0.0	0.0	0.6	-1.7	-1.2	2.8	-0.7	0.0
Conservation	0.8	0.0	-0.1	-4.5	-0.5	-1.2	5.8	0.0	0.0
Biofuels	0.0	0.0	0.0	11.7	-10.5	-5.6	5.7	0.0	0.0

Figure 16. Summary of land use and land cover changes for five different scenarios in Třeboň Basin BR by 2050.
(Source: Author's elaboration)

3.2.2 Šumava Biosphere Reserve

Figure 17 presents the spatial pattern of LULC change in Šumava BR in 2050 for three different LULC scenarios. The LULC proportions in the baseline landscape (2006) and each of the scenarios is provided in Table 15. The aggregate proportion of land undergoing LULC change between 2006 and 2050 in Šumava BR is 10% for the Green scenario, 8% for the Red scenario and 3% for the Shared vision.

The results indicate that under all five LULC scenarios, there is an increasing trend in urban areas and a decreasing trend in pastures. The quality of LULC change under each scenario differed substantially (Figure 18). The total area of forests increased by 9.8% under the Green scenario, mainly in the non-intervention parts of NP Zone I, replacing earlier successional stages of forest and shrub land. On the contrary, in the Red scenario, forested areas decreased by 7.6% as a result of transformation to pastures and principally agricultural land in the peripheral parts of Šumava. The slightly increased proportion of area occupied by sport facilities under the Red scenario corresponds to the construction of a ski resort and several small-scale artificial water reservoirs, while the increase in pastures under this scenario reflects the preference for more intensive land uses generating economic revenues.

While the area of natural LULC types (forests, natural grasslands, marshes and peat bogs) increased by 5.0% under the Green scenario, it decreased by 6.8% under the Red scenario. The smallest change in the proportion of different LULC categories occurred under the Shared vision, since this scenario supposed a focus on the preservation of current landscape values and moderate sustainable development.

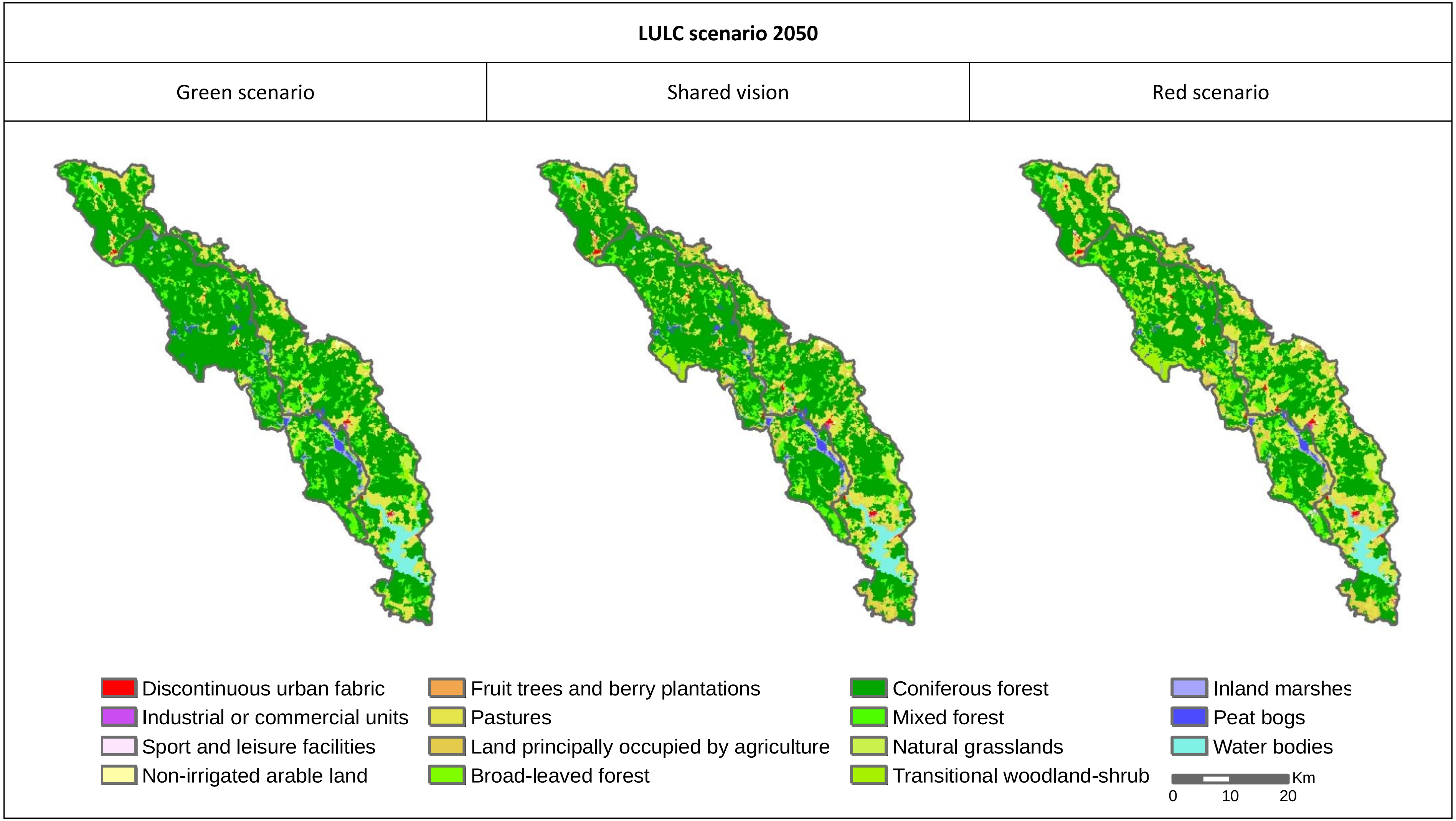
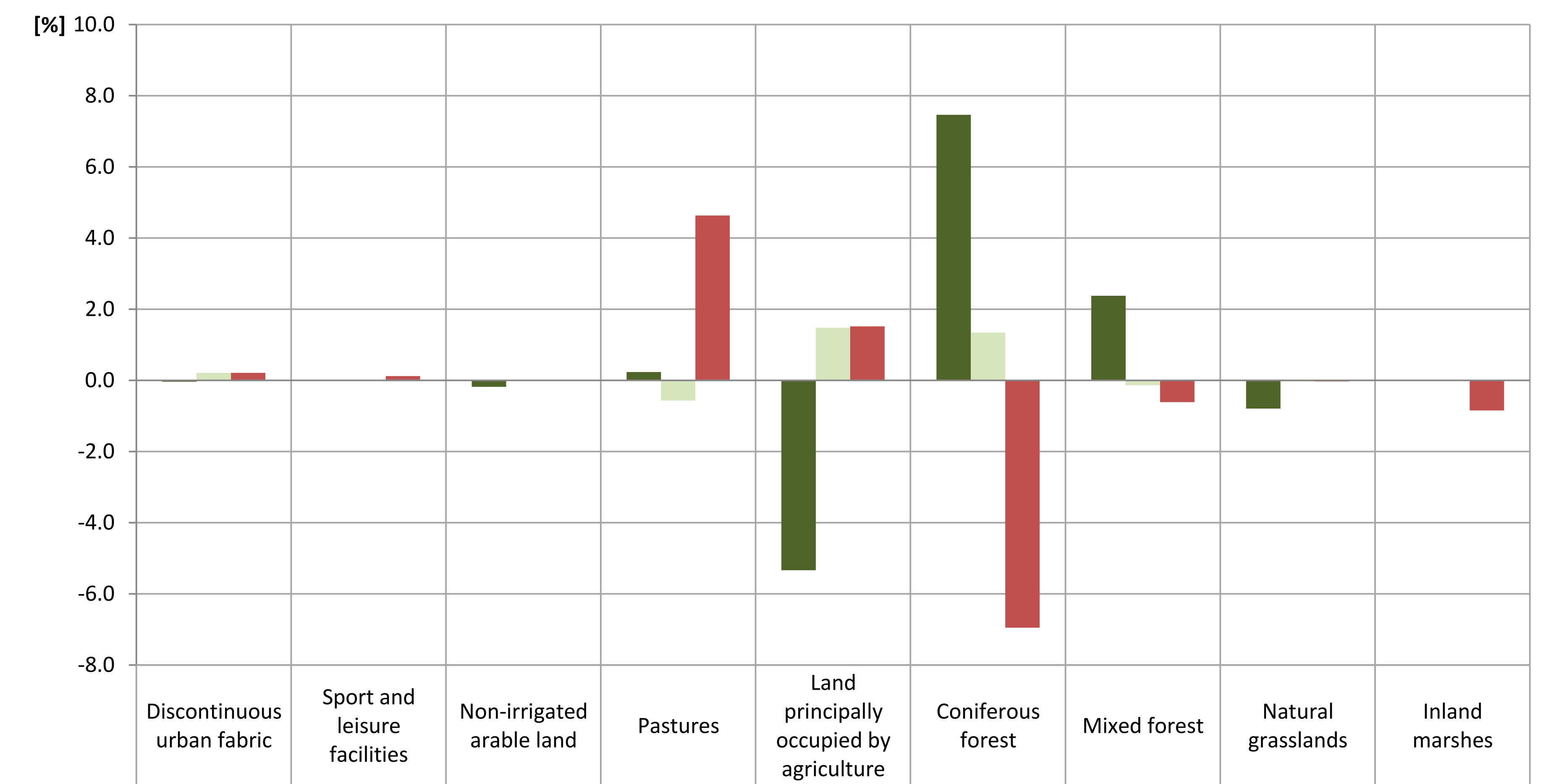


Figure 17. Land use and land cover change scenarios for Šumava BR in 2050, corresponding to stakeholder storylines.
(Source: Author's elaboration)

Table 15. Proportions of land use and land cover types in Šumava BR in the baseline year (2006) and in three scenarios to 2050. The total area of Šumava BR is approximately 170,000 ha.

	Area							
	Baseline (2006)		Green scenario		Shared vision		Red scenario	
	[ha]	[%]	[ha]	[%]	[ha]	[%]	[ha]	[%]
Discontinuous urban fabric	818	0.5	747	0.4	1,166	0.7	1,173	0.7
Industrial or commercial units	127	0.1	125	0.1	125	0.1	125	0.1
Sport and leisure facilities	157	0.1	154	0.1	154	0.1	352	0.2
Non-irrigated arable land	793	0.5	486	0.3	777	0.5	791	0.5
Fruit trees and berry plantations	136	0.1	14	0.0	140	0.1	126	0.1
Pastures	24,041	14.4	24,432	14.6	23,095	13.8	31,792	19.0
Complex cultivation patterns	3	0.0	0	0.0	1	0.0	1	0.0
Land principally occupied by agriculture	9,513	5.7	589	0.4	11,979	7.2	12,050	7.2
Broad-leaved forest	1,011	0.6	1,009	0.6	990	0.6	920	0.6
Coniferous forest	98,834	59.1	111,316	66.6	101,078	60.4	87,202	52.1
Mixed forest	9,900	5.9	13,877	8.3	9,671	5.8	8,869	5.3
Natural grasslands	4,009	2.4	2,675	1.6	3,957	2.4	3,957	2.4
Transitional woodland-shrub	10,374	6.2	3,600	2.2	5,891	3.5	13,356	8.0
Inland marshes	2,601	1.6	2,589	1.5	2,589	1.5	1,190	0.7
Peat bogs	1,497	0.9	1,497	0.9	1,497	0.9	1,177	0.7
Water bodies	4,138	2.5	4,138	2.5	4,138	2.5	4,167	2.5



	Discontinuous urban fabric	Sport and leisure facilities	Non-irrigated arable land	Pastures	Land principally occupied by agriculture	Coniferous forest	Mixed forest	Natural grasslands	Inland marshes
Green	0.0	0.0	-0.2	0.2	-5.3	7.5	2.4	-0.8	0.0
Shared	0.2	0.0	0.0	-0.6	1.5	1.3	-0.1	0.0	0.0
Red	0.2	0.1	0.0	4.6	1.5	-7.0	-0.6	0.0	-0.8

Figure 18. Summary of land use and land cover changes for three different scenarios in Šumava BR by 2050.
(Source: Author’s elaboration)

3.3 Ecosystem services assessment

3.3.1 Třeboň Basin Biosphere Reserve

3.3.1.1 Crop production

Crop production was assessed based on the aggregate area of Non-irrigated arable land present in Třeboň Basin BR under different scenarios in 2050. The proportion of Non-irrigated arable land (Table 14, Table 16) was highest under the Biofuels scenarios (31.2%), reflecting the emphasis on biofuel production in the scenario storyline, followed by the Exploitation scenario and the BaU scenario. The lowest levels of agricultural production were projected for the Market scenario (17.6%) and the Protection scenario (15.1%). In the case of the Market scenario, this is in line with the assumption of declining agricultural sector in Europe in the next few decades; for the Protection scenario, this reflects the tendency to abandon intensive land use types and to prefer non-exploitative activities in the study area.

The spatial pattern of temporal changes in crop production between 2006 and 2050 (Figure 19) illustrate the vast increase in arable land in the Biofuels scenario and net decrease in agricultural land in the Conservation scenario. The remaining three scenarios show mixed trends, where intensively managed agricultural land increases mainly in the neighbourhood of municipal areas and replace former pastures and less intensive agricultural types.

3.3.1.2 Timber production

Timber production was assessed based on the aggregate area of Broad-leaved forest, Coniferous forest and Mixed forest land present in Třeboň Basin BR under different scenarios in 2050 (Table 14, Table 16). The area of forests resulted in an approximately equal proportion (ca 55%) under the Conservation, the Market and the Biofuels scenarios, in all cases representing an approximately 5% increase in comparison with the baseline landscape. On the contrary, the Exploitation scenario (41.4% of forests) shows 8% decrease in timber-producing areas.

The spatial pattern of temporal changes in timber production between 2006 and 2050 (Figure 19) show increases and decreases of forest areas on current forest fringes, with forest cover replacing Transitional woodland-shrubs, Pastures and various types of agricultural land (and vice versa).

Table 16. Aggregate characteristics of provisioning ecosystem services (crop and timber production) in Třeboň Basin BR for the baseline (2006) and five scenarios to 2050.

	Total arable land [ha]	**Change in crop production** [%]
Baseline (2006)	13,446	0.0
Market	12,108	-10.0
Exploitation	17,040	26.7
BaU	13,842	2.9
Conservation	10,362	-22.9
Biofuels	21,456	59.6
	Total forests [ha]	**Change in timber production** [%]
Baseline (2006)	33,819	0.0
Market	37,759	11.7
Exploitation	28,483	-15.8
BaU	35,285	4.3
Conservation	37,802	11.8
Biofuels	37,408	10.6

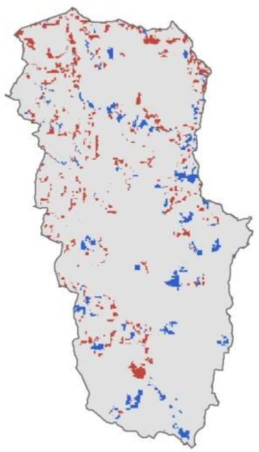
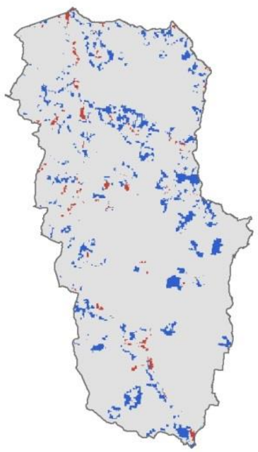
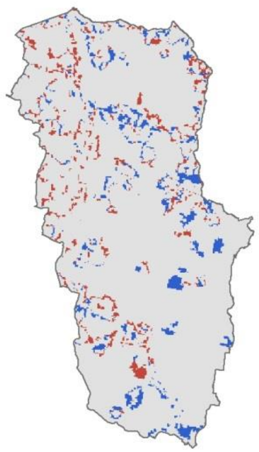
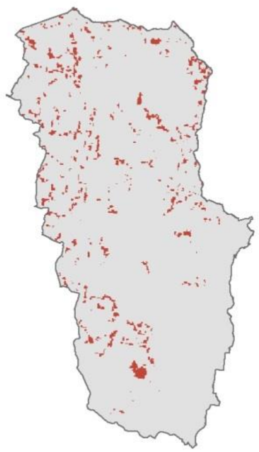
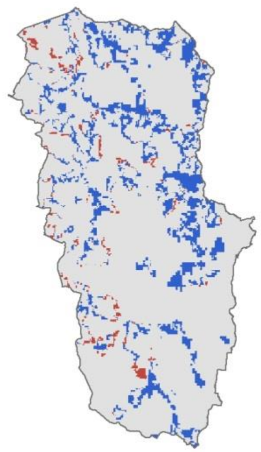
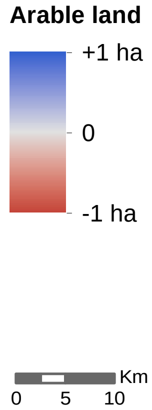
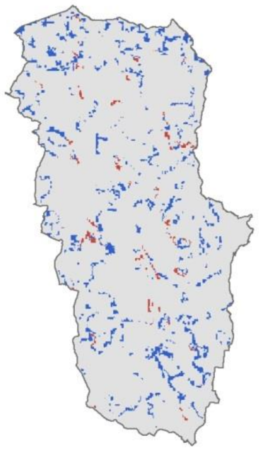
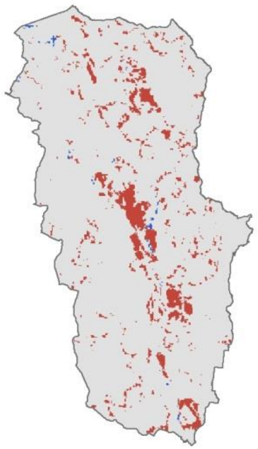
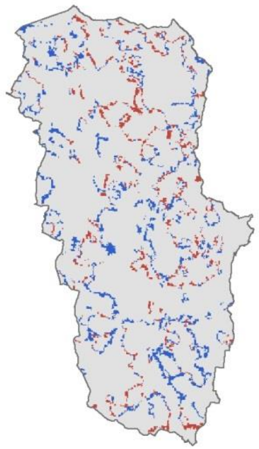
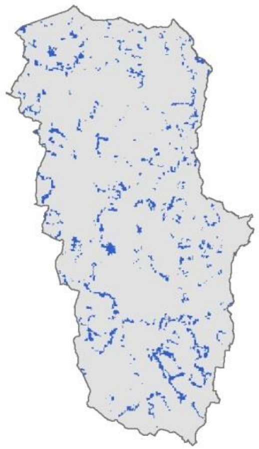
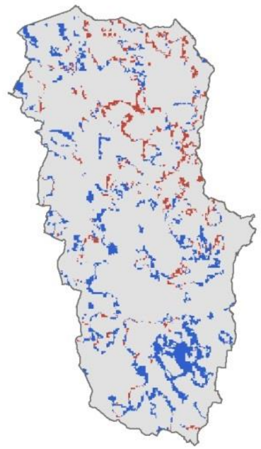
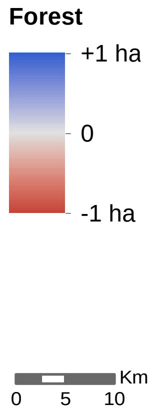
ES	Scenario 2006 – 2050					Legend
	Market	Exploitation	BaU	Conservation	Biofuels	
Crop production						
Timber production						

Figure 19. The spatial pattern of change in the provision of provisioning ecosystem services (crop production and timber production) in Třeboň Basin BR for five scenarios to 2050 (in comparison with the baseline).
(Source: Author's elaboration)

3.3.1.3 Climate regulation

Climate regulation was assessed as the amount of carbon stored in ecosystems in the study area under different scenarios. The baseline level of carbon storage in 2006 was 124 t ha^{-1} (Table 17). In 2050, the modelled level of carbon storage increased in the majority of the scenarios to 126-131 t ha^{-1}, while in the Exploitation scenario, it decreased to 108 t ha^{-1}. The highest level of carbon storage was reached under the Conservation scenario (5.3% improvement of carbon stocks), while the Exploitation scenario lead to 13.6% decrease in carbon stocks.

In terms of spatial patterns (Figure 20), the most substantial changes in carbon storage in all scenarios resulted from the variation in forests and arable land, on the fringes of current forests and in the neighbourhood of municipalities. The most distinctive pattern is present in the case of the Exploitation scenario, where the losses of carbon occur as a result of intensifying mining activities and the increase in agricultural land.

3.3.1.4 Water quality: Nitrogen

Concerning the ecosystem service of water quality regulation through nitrogen retention, we assessed the change in nitrogen export to streams between the baseline and the five scenarios (Table 17). While the baseline annual nitrogen export was 0.80 kg ha^{-1} $year^{-1}$, it decreased to 0.46 kg ha^{-1} $year^{-1}$ in the Conservation scenario, followed by 0.71 kg ha^{-1} $year^{-1}$ in the Biofuels scenario, corresponding to 42% and 11% decrease, respectively. On the contrary, nitrogen export increased to 1.16 kg ha^{-1} $year^{-1}$ in the Exploitation scenario (44.9% increase), as a result of higher nitrogen loading from intensively managed fish-ponds, combined with a decreasing capacity of the landscape to retain nitrogen.

In terms of spatial patterns (Figure 20), increasing nitrogen export was most evident in subwatersheds with diminishing forest cover and increasing proportion of arable land, such as in the case of the Biofuels scenario, where the subwatersheds with increasing nitrogen export in the north-east reflect the areas with expanding areas of arable land. The overall decrease in nitrogen export in the Conservation scenario reflects the aggregate increase in forested land and reduced nitrogen loading from fish-ponds.

3.3.1.5 Water quality: Sediments

The ecosystem service of water quality regulation through sediment retention was assessed as the change in sediment export to streams between the baseline and the five scenarios

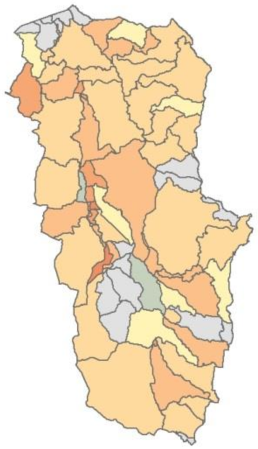
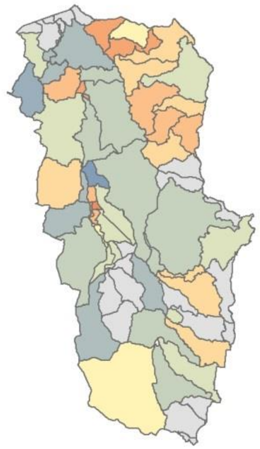
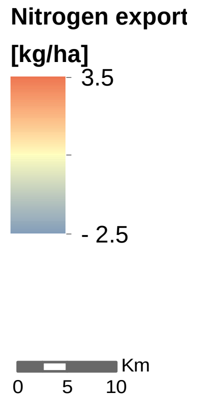
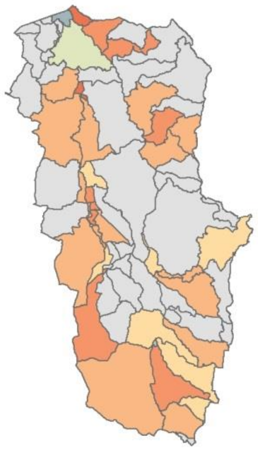
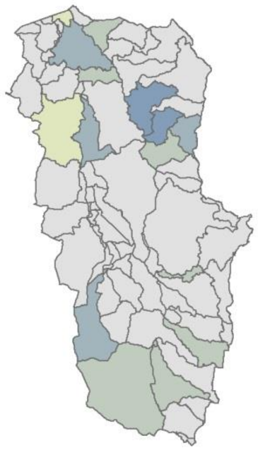
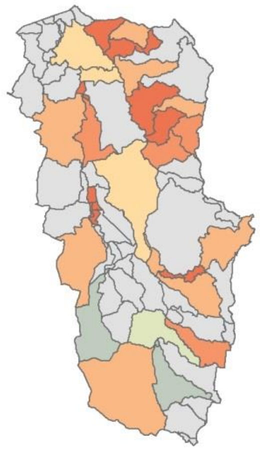
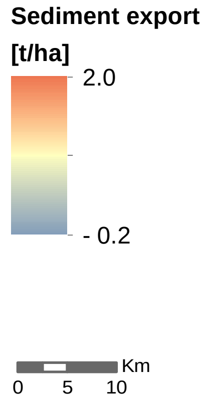
(Table 17). In general, the level of soil erosion was very low in the study area, mainly due to its lowland character; therefore, the resulting export of sediments to streams modelled reached only negligible levels. In comparison with the baseline sediment export (0.034 t ha^{-1} year^{-1}), the Market and the Conservation scenario were characterized by decreasing sediment export (0.026 t ha^{-1} year^{-1} and 0.021 t ha^{-1} year^{-1}, respectively). In both cases, this trend was caused by the abandonment of arable land and its transformation to pastures and forests. On the contrary, the Biofuels and the Exploitation shows substantial increase in sediment export, reaching 50-68% increase resulting from the expansion of arable areas and agricultural intensification.

In terms of spatial patterns (Figure 20), the most distinctive trends were (a) the increase in sediment export in the south-west of the study area in the Exploitation scenario, and (b) the increase in sediment export in the north-west of the study area in the Biofuels scenario. While the former case was already explained above by the increase in arable land, the letter case was caused by the degradation of nutrient-retaining wetlands and their replacement by mining areas.

Table 17. Aggregate characteristics of regulating ecosystem services (climate regulation and water quality regulation) in Třeboň Basin BR for the baseline (2006) and five scenarios to 2050.

	Total carbon storage [t]	Average carbon storage [t ha^{-1}]	Change in carbon storage [%]
Baseline (2006)	8,542,000	124	0.0
Market	8,953,000	130	4.8
Exploitation	7,382,000	108	-13.6
BaU	8,626,000	126	1.0
Conservation	8,994,000	131	5.3
Biofuels	8,904,000	130	4.2
	Total nitrogen export to streams [kg year^{-1}]	**Average nitrogen export to streams** [kg ha^{-1} year^{-1}]	**Change in nitrogen export to streams** [%]
Baseline (2006)	54,900	0.80	0.0
Market	60,400	0.88	10.0
Exploitation	79,600	1.16	44.9
BaU	54,000	0.79	-1.7
Conservation	31,900	0.46	-42.0
Biofuels	48,900	0.71	-11.0

	Total sediment export to streams [t $year^{-1}$]	Average sediment export to streams [t ha^{-1} $year^{-1}$]	Change in sediment export to streams [%]
Baseline (2006)	2,300	0.034	0.0
Market	1,800	0.026	-23.2
Exploitation	3,500	0.051	50.3
BaU	1,900	0.028	-17.5
Conservation	1,500	0.021	-37.7
Biofuels	4,000	0.058	68.2

ES	Scenario 2006 – 2050					Legend
	Market	Exploitation	BaU	Conservation	Biofuels	
Water quality: Nitrogen						
Water quality: Sediments						

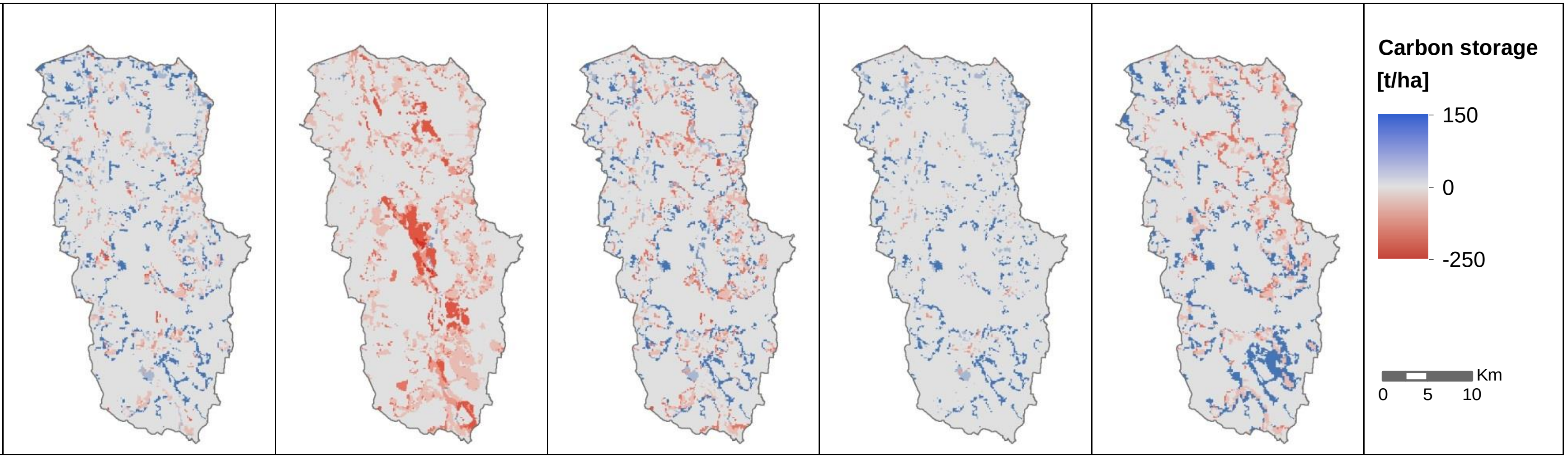
Climate regulation	

Figure 20. The spatial pattern of change in the provision of regulating ecosystem services (water quality regulation and climate regulation) in Třeboň Basin BR for five scenarios to 2050 (in comparison with the baseline).
(Source: Author's elaboration)

3.3.1.6 Recreation potential

The ecosystem service of recreation was assessed using the recreation potential index (RPI), reaching values on a relative scale 0-1 (Table 18). While most scenarios were characterized by limited difference from the baseline (RPI = 0.551), a substantial decrease in RPI was encountered in scenarios with market and economic incentives as the predominant driving forces influencing the landscape (the Exploitation and the Market scenario). In both cases, the recreation potential of the area was decreased by intensified use of fish-ponds, which hampered their use as recreational sites. In the case of the Exploitation scenario, a further exacerbation of the trend was caused by agricultural intensification and the expansion of arable land. An increase in RPI occurred in the Conservation and the Biofuels scenarios. While in the Conservation scenario, this was mainly caused by decreasing intensity of fishing industry and a higher recreational potential of the ponds, in the case of the Biofuels scenario, the trend resulted from an overall enlargement of landscape patches, ensuring higher landscape connectivity (Figure 21).

3.3.1.7 Landscape aesthetics

The cultural ecosystem service of landscape aesthetics was assessed applying the landscape aesthetics index (LAI), reaching values on a relative scale 0-1 (Table 18). The highest values of LAI were reached under the Conservation and the Markets scenarios (LAI = 0.392 in both cases), as a result of expanding forest ecosystems and the enlargement of forest patches (Figure 21). While the baseline and the BaU scenario scored moderate values of LAI (LAI_{2006} = 0.368 and LAI_{BaU} = 0.369), the Exploitation and the Biofuels scenarios were characterized by decreasing LAI (to 0.345 and 0.356, respectively), mainly as a result of land-use intensification in the study area. Nevertheless, the aggregate level of change was limited for all scenarios, not exceeding 5% change in comparison with the baseline.

Table 18. Aggregate characteristics of cultural ecosystem services (recreation potential and landscape aesthetics) in Třeboň Basin BR for the baseline (2006) and five scenarios to 2050.

	Average recreation potential index (RPI) [0-1 scale]	Change in RPI [%]	Average landscape aesthetics index (LAI) [0-1 scale]	Change in LAI [%]
Baseline (2006)	0.511	0.0	0.368	0.0
Market	0.482	-5.5	0.392	4.0
Exploitation	0.339	-32.3	0.345	-4.1
BaU	0.516	0.8	0.369	0.2
Conservation	0.542	5.8	0.392	4.1
Biofuels	0.544	6.1	0.356	-2.0

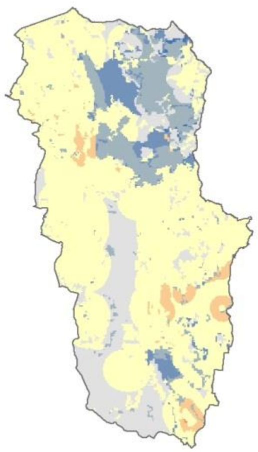
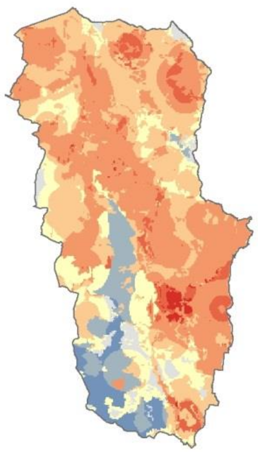
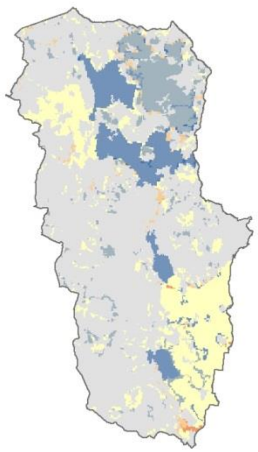
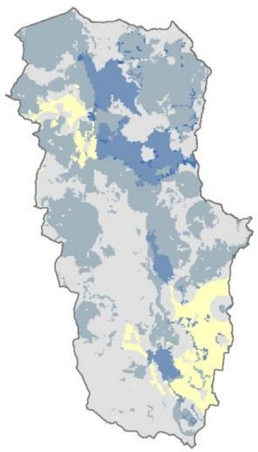
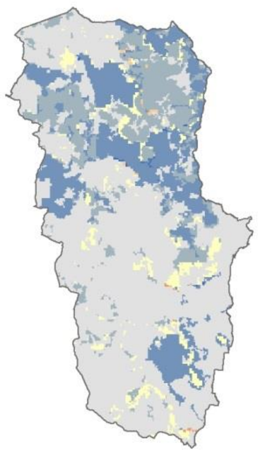
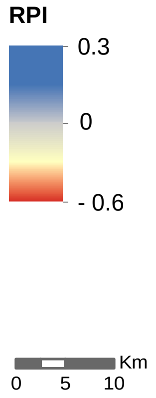
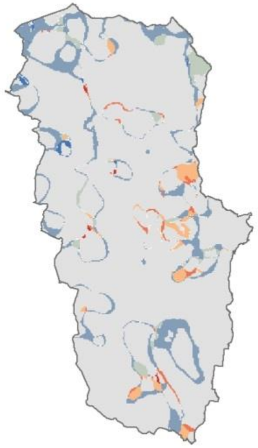
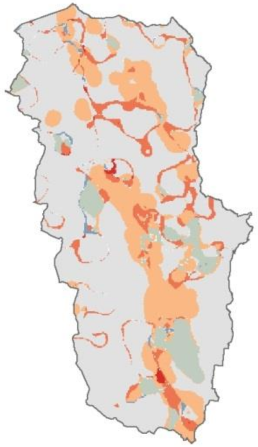
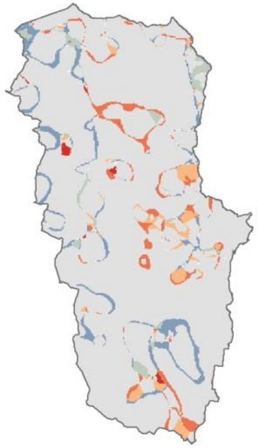
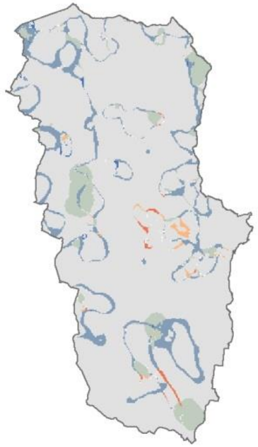
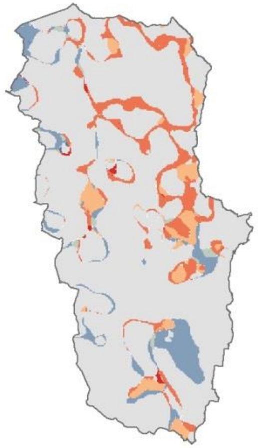
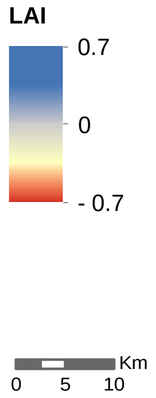
ES	Scenario 2006 – 2050					Legend
	Market	Exploitation	BaU	Conservation	Biofuels	
Recreation potential						
Landscape aesthetics						

Figure 21. The spatial pattern of change in the provision of cultural ecosystem services (recreation potential and landscape aesthetics) in Třeboň Basin BR for five scenarios to 2050 (in comparison with the baseline).
(Source: Author's elaboration)

3.3.2 Šumava Biosphere Reserve

3.3.2.1 Hydropower production

Since Šumava BR presents an important part of the Lipno reservoir watershed, one of the ES modelled in this case study area was the contribution of the water-yield from local ecosystems to hydropower production (Table 19). While the average contribution to hydropower production was 1,890 kWh ha^{-1} year^{-1} in the baseline landscape, it decreased by 1.2% in the Green scenario (Figure 22). This trend was caused by the increase in forested area and consequent higher evapotranspiration, which resulted in smaller amounts of water reaching the streams and the Lipno reservoir. The contribution to hydropower production increased by 1.2% in the Red scenario, mainly due to an opposite trend in the proportion of forested area. However, it should be noted that the aggregate information on annual water-yields under different scenarios, projecting smaller water-yields in the Green scenario than in the Red scenario, does not reflect the generally positive influence of forest land cover on temporal stability of water-yield distribution throughout the year. The final contribution of water yield generated by the landscape to hydropower production varied between 1,868-1,912 kWh ha^{-1} year^{-1} under different scenarios.

Table 19. Aggregate characteristics of provisioning ecosystem services (hydropower production) in Šumava BR for the baseline (2006) and three scenarios to 2050.

	Total contribution to hydropower production [kWh year^{-1}]	Average contribution to hydropower production [kWh ha^{-1} year^{-1}]	Change in the contribution to hydropower production [%]
Baseline (2006)	132,584,000	1,890	0.0
Green scenario	131,016,000	1,868	-1.2
Shared vision	131,859,000	1,880	-0.5
Red scenario	134,115,000	1,912	1.2

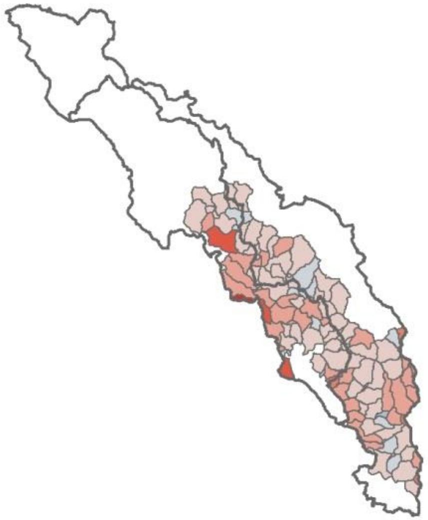
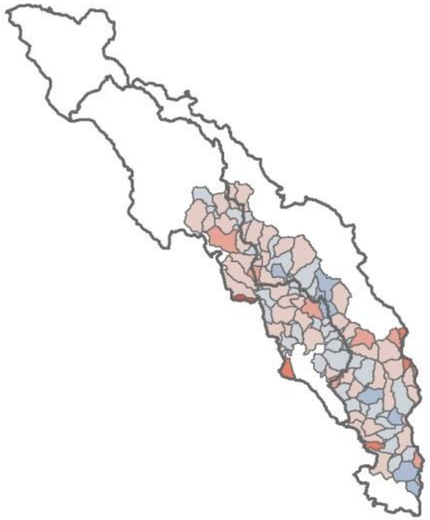
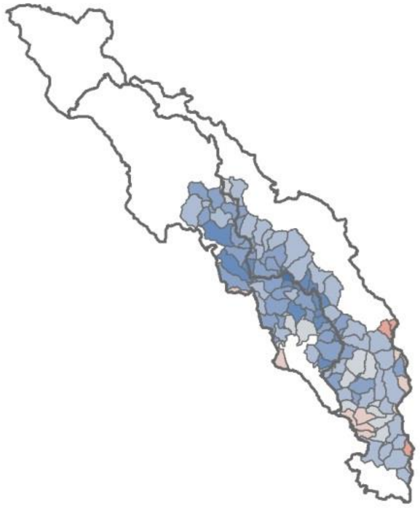
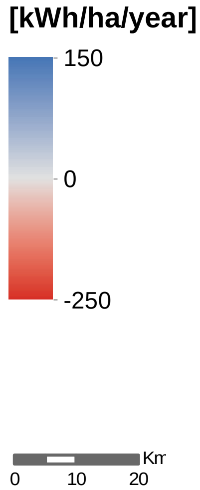
ES	Scenario 2006 – 2050			Legend
	Green scenario	Shared vision	Red scenario	
Hydropower production				

Figure 22. The spatial pattern of change in the provision of provisioning ecosystem services (hydropower production) in Šumava BR for three scenarios to 2050 (in comparison with the baseline).
(Source: Author's elaboration)

3.3.2.2 Climate regulation

Climate regulation represented by carbon storage in Šumava BR showed substantial differences between the scenarios (Table 20, Figure 23). The spatial pattern of change in carbon storage corresponded to areas where LULC category changed between the baseline landscape and scenarios. In the Green scenario, carbon storage increased by 7.4% to 163 t ha^{-1} between 2006 and 2050 as a result of forest growth and the enlargement of forested area. The increase in carbon stocks was less pronounced in the Shared vision (by 0.3% to 152 t ha^{-1}). On the contrary, carbon stocks decreased by 6.3% in the Red scenario, mainly due to timber logging and an increasing area of agricultural land. The average level of carbon storage under different scenarios varied between 142-163 t ha^{-1} (Table 20).

3.3.2.3 Water quality: Nitrogen

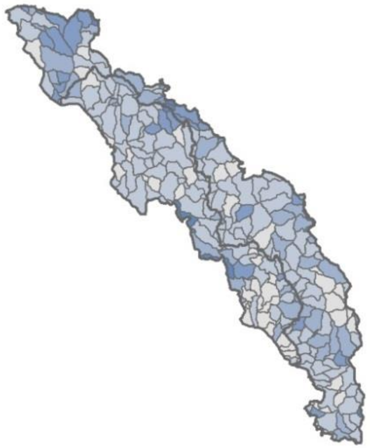
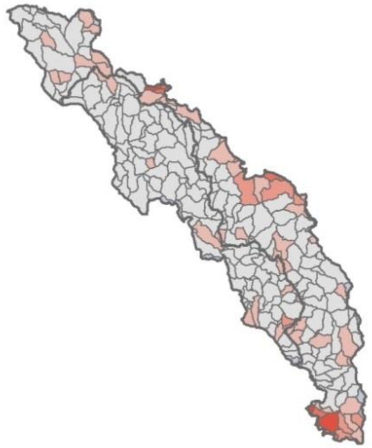
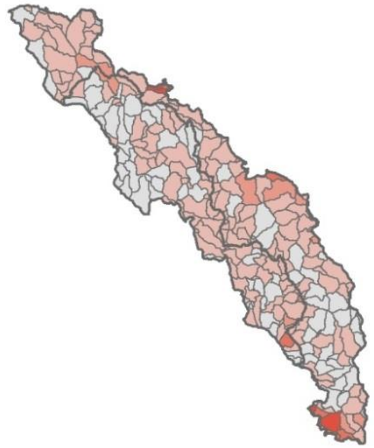
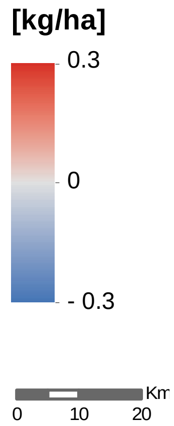
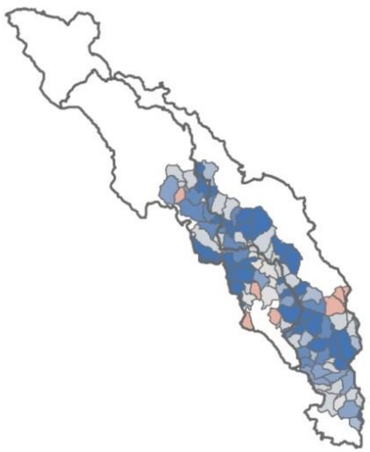
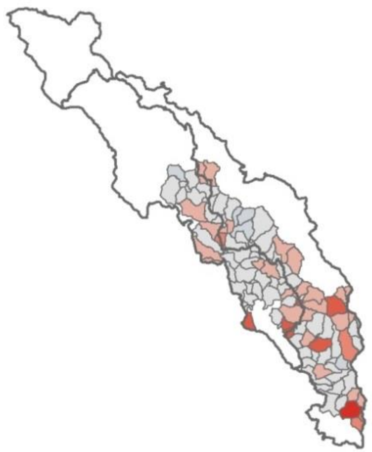
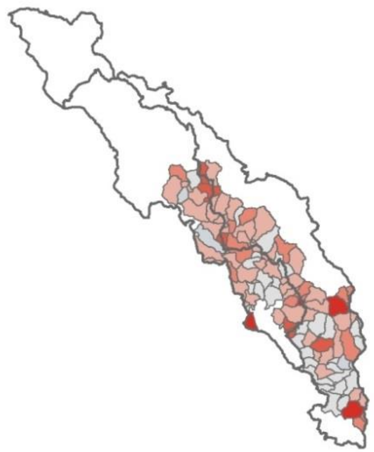
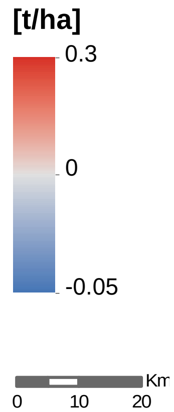
The ecosystem service of water quality regulation was assessed through the amount of nitrogen exported to streams. Table 20 indicates that the average level of nitrogen export decreased from 0.26 kg ha^{-1} $year^{-1}$ in the baseline landscape to 0.17 kg ha^{-1} $year^{-1}$ in the Green scenario. This trend resulted from the increase in forested area, since nitrogen loading from forests is generally low, and at the same time, forests land efficiently retains nitrogen from water run-off. In the Red scenario, nitrogen export increased to 0.31 kg ha^{-1} $year^{-1}$, which can be attributed mainly to newly established agricultural areas in the north-eastern border parts of the study area. The most significant increase in nitrogen discharge occurred in the southern part of the study location under the Red scenario, due to the construction of a new ski resort and related accommodation capacities and infrastructure (Figure 23).

3.3.2.4 Water quality: Sediments

In line with the previous section, another aspect of water quality regulation was examined through the amount of sediments retained by ecosystems, thus decreasing the final export of sediments to streams. Trends similar to nitrogen export were present in the case of sediment export, since both these variables are influenced by similar types of LULC change (Figure 23). For the Green scenario, Shared vision and Red scenario, the average level of sediment export were 0.02 t ha^{-1} $year^{-1}$, 0.09 t ha^{-1} $year^{-1}$ and 0.10 t ha^{-1} $year^{-1}$, respectively, in comparison with the baseline sediment export of 0.09 t ha^{-1} $year^{-1}$ (Table 20). Substantial decrease in sediment export under the Green scenario resulted from the abandonment of agricultural land and its transformation to forests and pastures (Figure 23).

Table 20. Aggregate characteristics of regulating ecosystem services (climate regulation and water quality regulation) in Šumava BR for the baseline (2006) and three scenarios to 2050.

	Total carbon storage [t]	Average carbon storage [t ha^{-1}]	Change in carbon storage [%]
Baseline (2006)	25,506,000	152	0.0
Green scenario	27,392,000	163	7.4
Shared vision	25,576,000	152	0.3
Red scenario	23,890,000	142	-6.3
	Total nitrogen export to streams [kg year^{-1}]	**Average nitrogen export to streams** [kg ha^{-1} year^{-1}]	**Change in nitrogen export to streams** [%]
Baseline (2006)	18,100	0.26	0.0
Green scenario	11,900	0.17	-34.3
Shared vision	18,800	0.27	3.9
Red scenario	22,000	0.31	21.5
	Total sediment export to streams [t year^{-1}]	**Average sediment export to streams** [t ha^{-1} year^{-1}]	**Change in sediment export to streams** [%]
Baseline (2006)	6,120	0.09	0.0
Green scenario	1,450	0.02	-76.3
Shared vision	6,260	0.09	2.3
Red scenario	6,690	0.10	9.3

ES	Scenario 2006 – 2050			Legend
	Green scenario	Shared vision	Red scenario	
Water quality: Nitrogen				
Water quality: Sediments				

Climate regulation

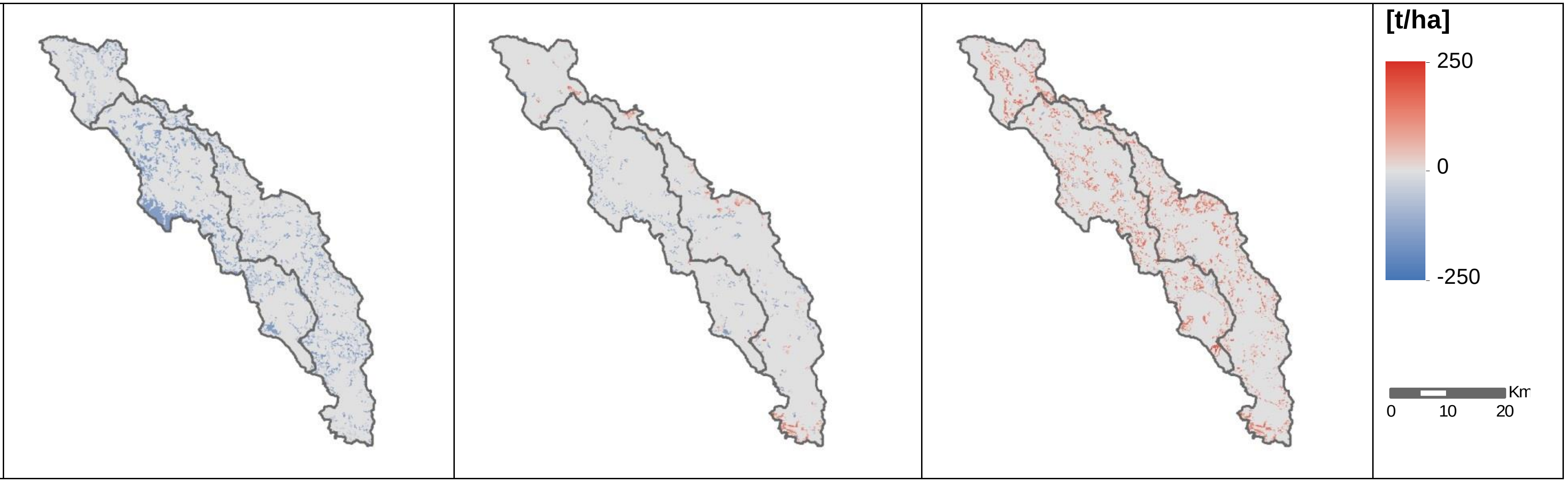


Figure 23. The spatial pattern of change in the provision of regulating ecosystem services (water quality regulation and climate regulation) in Šumava BR for three scenarios to 2050 (in comparison with the baseline).
(Source: Author's elaboration)

3.3.2.5 Recreation potential

To assess the ecosystem service of nature-based recreation, we used the recreation potential index (RPI), reaching values on a relative scale 0-1 (Table 21). The baseline landscape was characterized by a moderate RPI (RPI = 0.443).

A substantial decrease in RPI was encountered in the Red scenario (RPI = 0.398), characterized by low environmental concern. The main reasons for decreasing RPI in the Red scenario were (1) exacerbation of the condition of water bodies (including the negative impacts of intensive tourism in the surroundings of the Lipno reservoir), (2) wetland degradation and regression, (3) reduction in the area of natural forests and fragmentation of forest patches, (4) increase in built-up areas, and (5) weakened nature protection (Figure 24).

On the other hand, the Green scenario, assuming intensified nature protection as the predominant driving force influencing the landscape, accounted for RPI = 0.511. The increase in RPI was influenced by (1) improving ecological condition of natural water bodies (e.g. local glacier lakes) and (2) enlargement of near-natural forests and enhanced forest connectivity, and (3) replacement of earlier successional stages (such as transitional woodland and shrubs) by mature forests, representing three aspects attracting nature-oriented tourists. On the other hand, in some areas, the RPI under the Green scenario decreased as a result of reduction or replacement of originally non-forested, but valuable, habitats (such as natural grasslands) by forested land cover (Figure 24).

The Shared vision was characterized by a marginal change in RPI (RPI = 0.451), influenced by trends similar to the Green scenario (Figure 24).

3.3.2.6 Landscape aesthetics

The cultural ecosystem service of landscape aesthetics was assessed using the landscape aesthetics index (LAI), reaching values on a relative scale 0-1 (Table 21), and reflecting mainly the character of LULC change and the extent of anthropogenic activities in the landscape. In general, landscape aesthetics were assessed to undergo only minor changes in the time span from 2006 to 2050 (from -2.6% to 1%). The highest values of LAI were reached under the Green scenarios (LAI = 0.353), as a result of increased forest connectivity and enlargement of forest patches, as well as the promotion of development towards natural forest character. Interestingly, several areas were characterized by a decreasing LAI (Figure 24), due to an extensive transformation of land principally occupied by agriculture to pastures, which decreased the heterogeneity of the landscape. The baseline landscape and the Shared vision scored moderate values of LAI (both LAI = 0.348, 0.2% change). A decrease in LAI occurred under the Red scenario (to 0.329), mainly resulting from a transition of forest land to pastures and transitional forest succession stages. In addition, the expansion of built-up areas and the construction of large-scale sports and recreational facilities in the Klápa-Hraničník area further negatively influenced LAI in the Red scenario.

Table 21. Aggregate characteristics of cultural ecosystem services (recreation potential and landscape aesthetics) in Šumava BR for the baseline (2006) and three scenarios to 2050.

	Average recreation potential index (RPI) [0-1 scale]	Change in RPI [%]	Average landscape aesthetics index (LAI) [0-1 scale]	Change in LAI [%]
Baseline (2006)	0.443	0.0	0.348	0.0
Green scenario	0.511	14.5	0.353	1.0
Shared vision	0.451	1.8	0.348	0.2
Red scenario	0.398	-9.6	0.329	-2.6

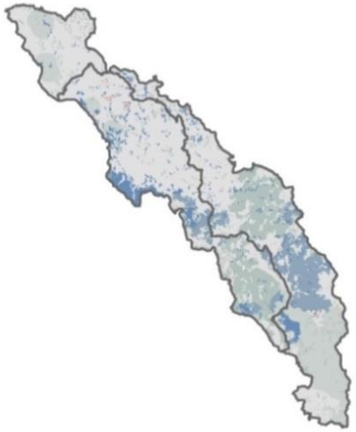
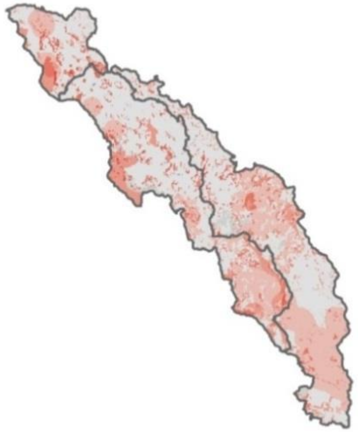
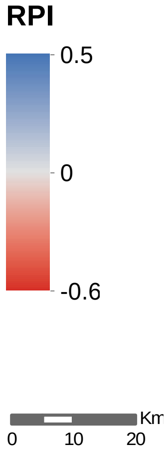
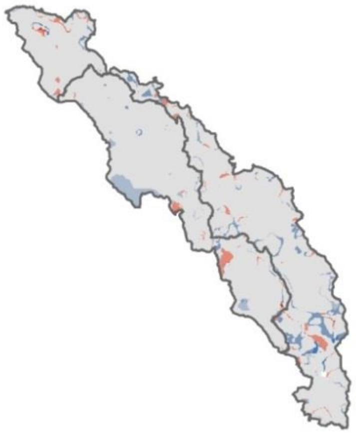
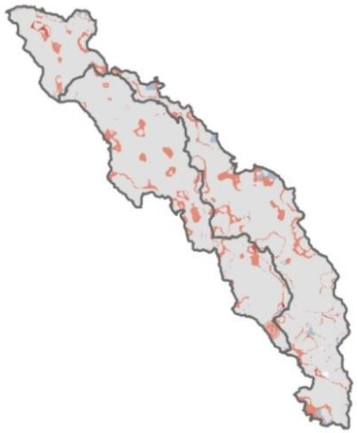
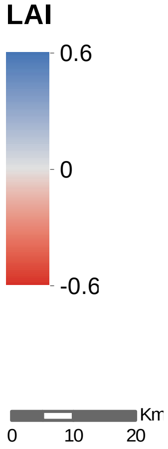
ES	Scenario 2006 – 2050			Legend
	Green scenario	Shared vision	Red scenario	
Recreation potential				
Landscape aesthetics				

Figure 24. The spatial pattern of change in the provision of cultural ecosystem services (recreation potential and landscape aesthetics) in Šumava BR for three scenarios to 2050 (in comparison with the baseline).

(Source: Author’s elaboration)

3.4 Trade-offs

The trade-offs between different types of ES in Třeboň Basin BR and Šumava BR were characterized by both quantitative and qualitative differences between scenarios. Figure 25 and Figure 27 provide the general comparison of the provision of ES under each scenario, also illustrating whether the overall level of ES provision increased or decreased between 2006 and 2050. Figure 26 and Figure 28 allow for the comparison of the provision of different types of ES, recalculated relatively according to a 1% change in climate regulation.

In general, most scenarios showed synergies between regulating ES (climate regulation, and water quality regulation in terms of nitrogen and sediment retention) in both the cases of Třeboň Basin and Šumava BRs. However, there were two exceptions, specifically in the cases of the Market and the Biofuels scenarios, in which the change in regulating services between 2006 and 2050 did not follow the same pattern, showing that while climate regulation increased, the provision of water-related regulating services followed mixed trends (Figure 25 – Figure 28).

Regarding provisioning ES, the results for Třeboň Basin BR show that crop production and timber production developed in an opposite direction in most scenarios, specifically those scenarios assuming a substantial LULC change (Conservation, Market, Exploitation). These results indicate that in the future, Třeboň Basin BR area might undergo a one-sided development decreasing the diversity of provided ES (Figure 25 and Figure 27). Synergies between cultural ES occurred in most of the scenarios, corroborating that aesthetically benign changes in landscape features and character are in turn beneficial for the nature-based recreational potential.

Figure 26 and Figure 28 illustrate the relative change in each studied type of ecosytsem service related to a 1% change in climate regulation, e.g. how many per cent increase or decrease a selected ES encountered while climate regulation changed by 1%. This approach facilitates to analyse the aspects of ES trade-offs not emerging from the general comparison, such as a more detailed analysis of the relationships between and within bundles of ES.

The results of this analysis further corroborate the above described findings that in general, synergies occur between ES within the groups of regulating services (such as between climate regulation and nitrogen retention) and cultural services (between landscape aesthetics and recreation potential). On the other hand, trade-offs between provisioning services (crop production and timber production) are present in most of the scenarios (Figure 26 and Figure 28).

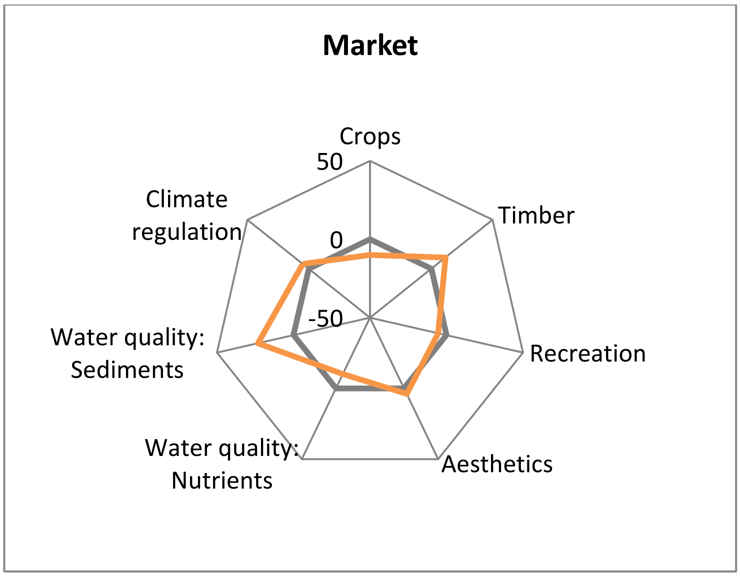
On the level of general classes of ES, in most cases, there is a synergy between regulating and cultural services (rendered in blue to red colour spectrum in Figure 26 and Figure 28). This result indicates that ecosystem changes enhancing the regulating functions of ecosystems (such as increased forest connectivity leading to higher climate regulation and nitrogen retention) tend to be concurrently beneficial in terms of intangible benefits derived from the ecosystems (e.g. aesthetic and recreational benefits).

On the other hand, mutual proportions between the magnitude and direction of changes in individual types of ES were not identical under different scenarios, not even between the services of the same class (i.e. provisioning, regulating and cultural). For instance, the relationship between two aspects of water quality regulation – nitrogen retention and sediment retention – differed both in terms of magnitude and in terms of direction under different scenarios (Figure 26 and Figure 28).

The magnitude and direction of change in a given ES compared to 1% change in climate regulation substantially differed among scenarios, e.g. the relative change in the provision of hydro-energy compared to a 1% change in climate regulation differed both quantitatively and qualitatively under different scenarios (Figure 28). Noticeably, the relative magnitude to which the aggregate provision of ES bundles changed compared to a 1% change in climate regulation differed substantially, revealing that the relationships between different types of ES are non-linear and their mutual proportions develop in a distinct pattern under different scenarios.

The most substantial aggregate increase in the provision of ES between 2006 and 2050 occured under the scenarios assuming intensive nature protection and focus on ecosystem conservation (the Conservation and the Green scenarios) (Figure 25 and Figure 27). On the contrary, the lowest aggregate provision of ES in 2050 was modelled for the scenarios assuming exploitative activities in the landscape and unsustainable economic growth (the Exploitation and the Red scenarios).

Interestingly, the aggregate level of change in ES for the Market scenario, the Biofuels scenario and the BaU scenario in Třeboň Basin BR, stemming from entirely different storylines and landscape development assumptions, is roughly similar. Generally, the Market and the Biofuels scenarios based on national to European-wide storylines showed much less substantial changes in the provision of ES than the Exploitation and Conservation storylines, vastly based on the local knowledge of participating stakeholders.


Market
Crops
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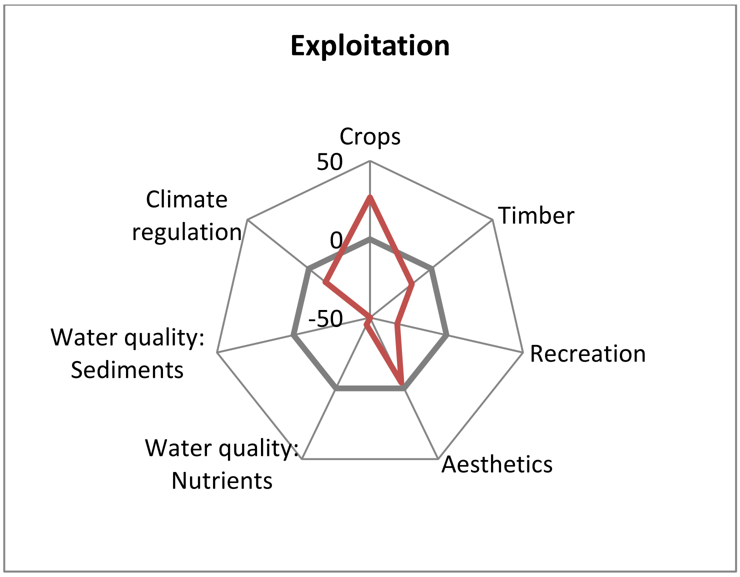
Timber
Recreation
Aesthetics
Water quality:
Nutrients
Water quality:
Sediments
Climate
regulation


Exploitation
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Water quality:
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Sediments
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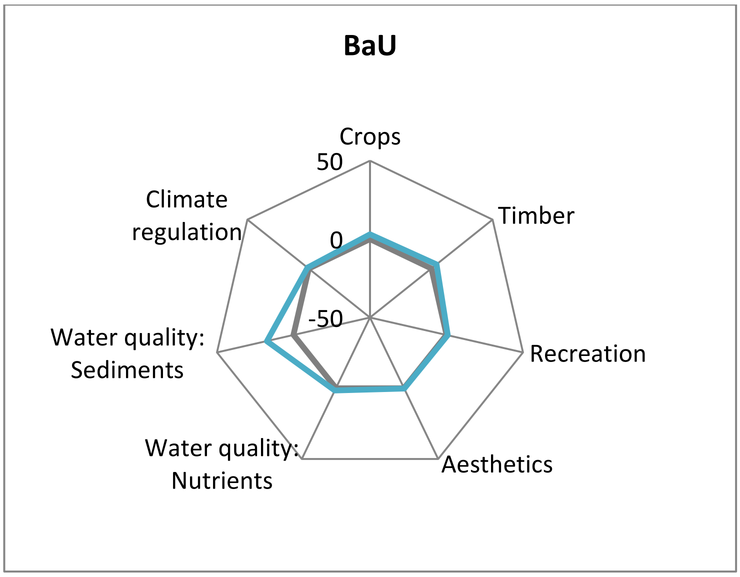
BaU
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Water quality:
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Water quality:
Sediments
Climate
regulation

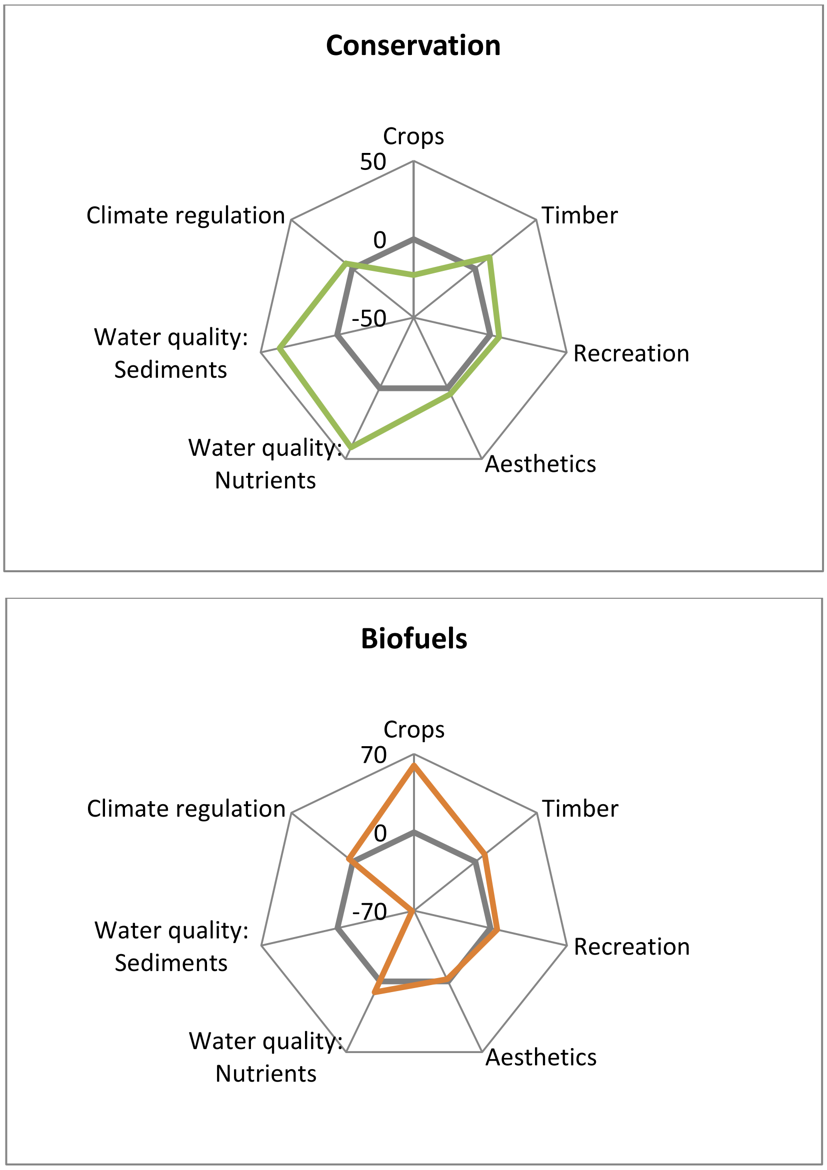
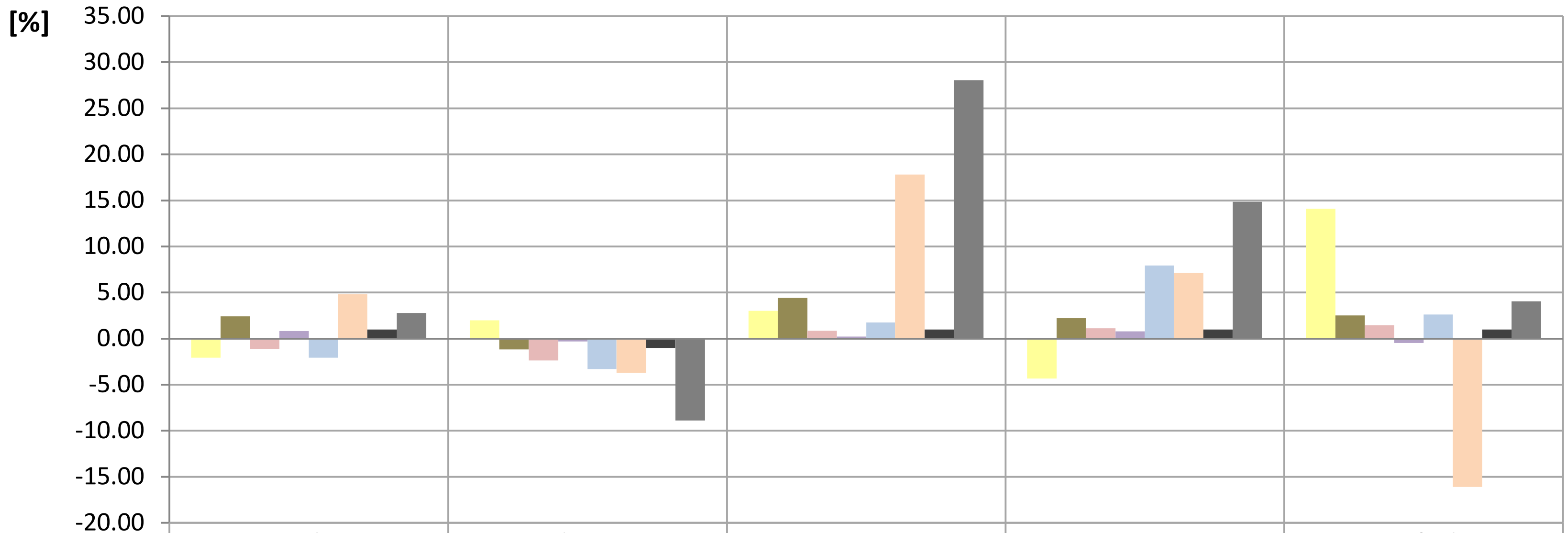


Figure 25. Illustration of trade-off types in Třeboň Basin BR under five scenarios by 2050: relative change in the provision of ecosystem services compared to 2006 [%]
(Source: Author's elaboration)



	Market	Exploitation	BaU	Conservation	Biofuels
Crops	-2.07	1.97	3.00	-4.34	14.08
Timber	2.42	-1.16	4.41	2.23	2.51
Recreation	-1.14	-2.38	0.84	1.10	1.45
Aesthetics	0.83	-0.30	0.20	0.78	-0.48
Water quality: Nutrients	-2.09	-3.31	1.76	7.94	2.60
Water quality: Sediments	4.82	-3.70	17.82	7.13	-16.12
Climate regulation	1	-1	1	1	1
Aggregate	2.78	-8.88	28.04	14.84	4.03

Figure 26. Trade-offs between ecosystem services in Třeboň Basin BR in 2050: change in the provision of ecosystem services relatively to a unit change (1%) in climate regulation [%].
(Source: Author's elaboration)

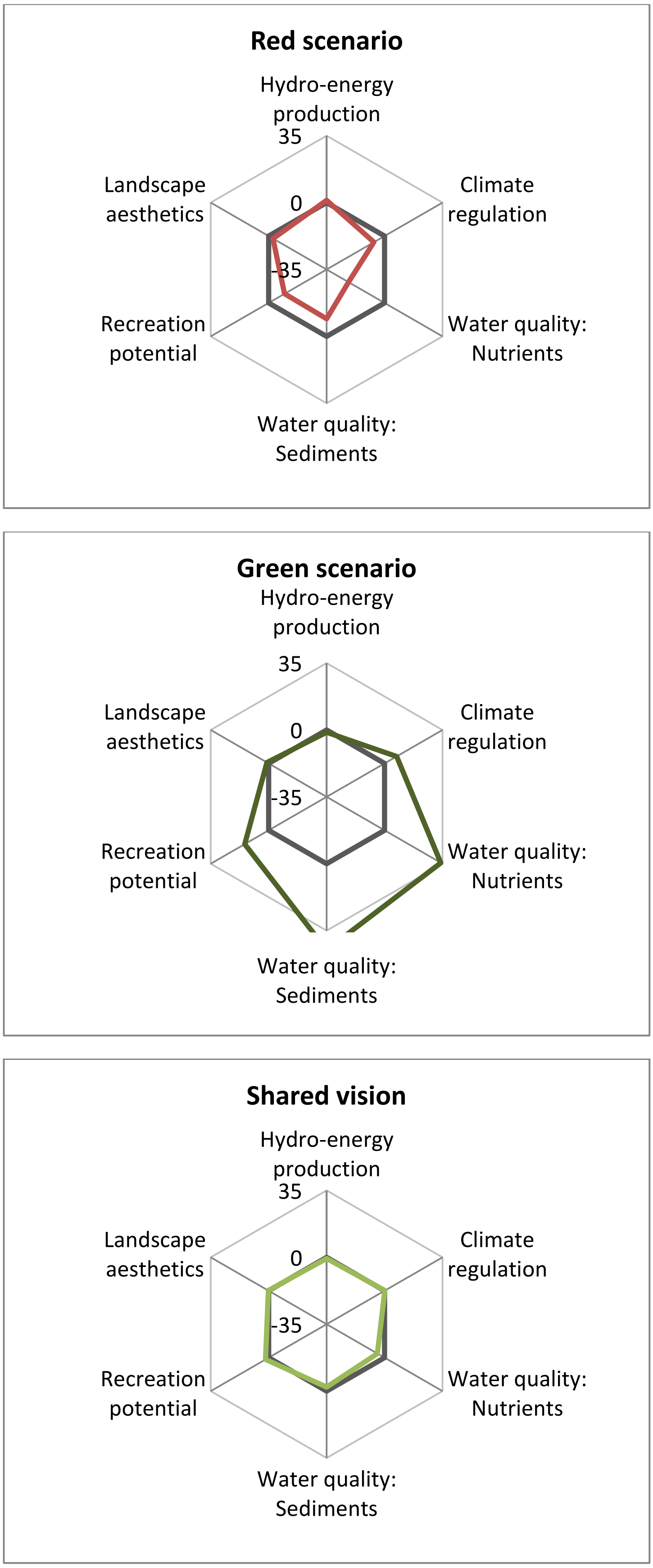
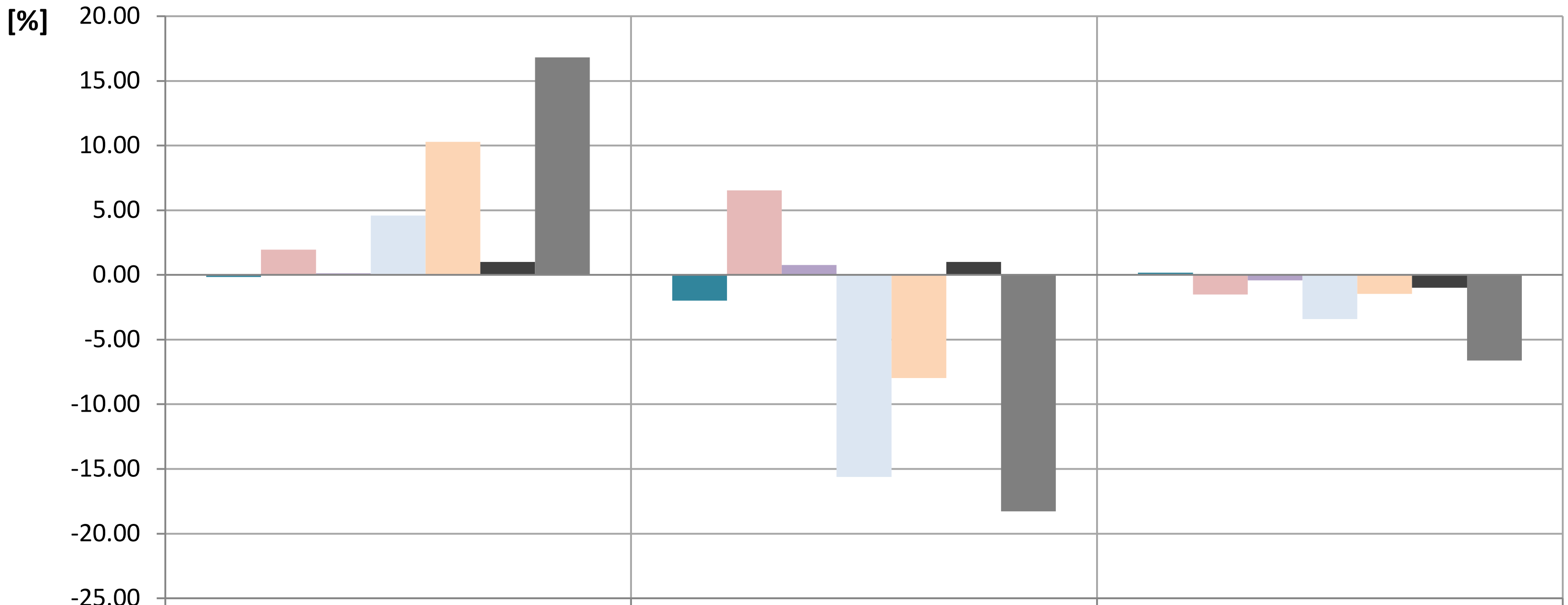


Figure 27. Illustration of trade-off types in Šumava BR under three scenarios by 2050: relative change in the provision of ecosystem services compared to 2006 [%]
(Source: Author's elaboration)



	Green scenario	Shared vision	Red scenario
Hydro-energy production	-0.16	-1.99	0.18
Recreation potential	1.96	6.55	-1.51
Landscape aesthetics	0.14	0.76	-0.42
Water quality: Nutrients	4.60	-15.61	-3.42
Water quality: Sediments	10.28	-7.97	-1.46
Climate regulation	1	1	-1
Aggregate	16.82	-18.26	-6.62

Figure 28. Trade-offs between ecosystem services in Šumava BR in 2050: change in the provision of ecosystem services relatively to a unit change (1%) in climate regulation [%].
(Source: Author's elaboration)

4 Discussion

The overarching aim of this thesis was to compile a coherent modelling approach to analyse SES dynamics – specifically, to assess potential changes in ES provision under diverse participatory scenarios of future LULC development. Subsequently, this participatory-based methodological approach was tested in selected SES, represented by Třeboň Basin and Šumava UNESCO Biosphere Reserves. In this section, we discuss the limitations of the applied approach and propose follow-up research steps.

4.1 Study approach and limitations

4.1.1 The concept of ecosystem services

This study utilized the concept of ES to support decision-making related to sustainable landscape management in the selected case study areas. Although originally, the concept of ES aimed to assist sustainable landscape management and biodiversity conservation, arguments have been raised recently that the anthropocentric ES perspective (focusing on the benefits for humanity) actually distracts from the mission of biodiversity conservation. Although this issue remains unresolved, it appears that in this respect, of main concern is an overly narrow interpretation of metrics and values for ES (Reyers et al., 2012).

Other critiques of the concept of ES include promotion of exploitative human-nature relationship and narrow focus on economic valuation. On the other hand, counter-arguments have been raised that the ES concept emphasizes humanity's dependence on nature and multiple types of values are incorporated in ES assessments (Schröter et al., 2014).

In addition, some studies argue that the substantial momentum the ES concept has gained tends to weaken other concepts promoting sustainable landscape management and biodiversity conservations, such as holistic ecosystem approach proposed by the Convention on Biological Diversity (Waylen et al., 2014).

4.1.2 Scenario approach

One of the fundamental parts of this study was creating scenarios of potential future LULC development. As the concept of scenarios often presents a subject of misunderstanding, we would like to emphasize that our understanding of scenario approach was in accord with Rounsevell and Metzger (2010); hence, we did not aim to create scenarios as forecasts of future landscape development; on the contrary, the scenarios in this study should be approached as extreme limits between which the real landscape development will probably occur. By the use of scenarios, we aimed to find probable boundaries of future landscape development and to assess the provision of ES within the interval defined by these boundaries (Goldstein et al., 2012; Lorencová et al., 2013).

Scenario approach presents an emerging method for the analysis of SES dynamics and participatory planning. For instance, a recent participatory case study conducted in southern Transylvania, Romania, employed scenarios to identify current and future risks and opportunities facing SES (Hanspach et al., 2014). Similarly to this thesis, the results suggested that the main opportunities for the future of the region lied in maintaining and carefully capitalizing on its high natural capital and cultural heritage, e.g. through promoting biodiversity conservation and eco-cultural tourism.

Additional European case studies illustrating the applications of place-based participatory scenario planning are included in a comprehensive review by Oteros-Rozas et al. (2015): e.g. the Peak District National Park in England (Reed et al., 2013), Doñana National Park (Palomo et al., 2011) and the Conquense Drove Road (Oteros-Rozas et al., 2013) in Spain, and the French Alps (Lamarque et al., 2013).

4.1.3 Stakeholder involvement and participatory approaches

Although current socio-ecological research widely recognizes the importance of transdisciplinary approaches, i.e. engaging stakeholders and general public at all stages of research projects, the involvement of stakeholders and application of participatory approaches are encumbered by substantial limitations (O'Farrell and Anderson, 2010; Rounsevell and Metzger, 2010; Roux et al., 2010; Harrison et al., 2013).

In general, it is rarely possible to involve an exhaustive sample of key stakeholders, due to limited research, time and economic capacity of research project, as well as professional and personal constraints on the side of the participants (Lamarque et al., 2013; Reed et al., 2013). Thus, although the number of participants in both of our case studies was limited, the majority of key stakeholders representing the most important landscape pressures in both case study areas were involved in the analysis. In the cases when key stakeholders were not willing to participate in the scenario building process (such as in the case of forestry and fish-farming sectors in Třeboň Basin BR), we substituted their input by eliciting plausible trends in these sectors from researchers involved in local hydrological, ecological and landscape research. Nevertheless, we acknowledge that failing to involve an exhaustive sample of stakeholders might have influenced the results of the analysis.

Consequently, it was not possible to apply the same approach of scenario building in both of the case studies. While in Šumava BR case study, additional funding and capacity was available to organize scenario building workshops, in Třeboň Basin BR case study, it proved unfeasible to assemble all the key stakeholders at a one-off meeting. Therefore, in the letter case, the approach of individual semi-structured interviews was applied as a substitute for group scenario building. Considering the final composition of participants in both case studies (for lists of participants, see the Methods section), it proved feasible to gain multiple scenario storylines from stakeholders of diverse background for subsequent analysis. Nevertheless, it should be noted that from the perspective of sustainable landscape management and decision-making, group scenario building presents a far more beneficial option, with a potential to create consensual scenarios and shared visions, such as in the case of Šumava BR.

Another issue inherent to participatory processes is based on the fact that all participants represent their personal and professional perspective parallelly (Metzger and Rounsevell, 2010). For instance, one participant may present interests and opinions of a local citizen and a free-time farmer, and a professional water manager at the same time. This issue may be mitigated by including more than one participant with the same professional background, so that it was possible to gain a more objective perspective on which aspects of participants' input are derived from their professional expertise, and which from their personal perspective. Nevertheless, it is generally impossible to avoid mixing personal and professional attitudes, which represents an unavoidable feature of the approach of participative scenario planning. However, this issue can also influence the information potential of the participatory process in a positive way, since the public opinion, represented by personal perspectives of local stakeholders, are highly valuable for the scenario building process.

Due to these issues, future collaboration with the stakeholders in both case study areas and potential update of the scenario storylines with input from additional stakeholders represent potential next steps of this research.

This thesis illustrates that local knowledge by involved stakeholders can serve as a productive input into the process of scenario building and related ES assessment. The involvement of local stakeholders brings added value to scenario development and subsequent GIS modelling by proposing alternatives informative and relevant for local decision-making (Reed et al., 2013). Through the process of scenario workshops and individual discussions, the stakeholders were motivated to take active part in scenario building and to become familiar with the concepts of ES and trade-offs. Thus, the study design successfully served awareness-raising purposes. However, at the same time, the study highlighted differences between locally-based knowledge and scientific findings. For instance, some stakeholders preferred the exploitative scenarios, assuming they will generate short-term economic revenues. However, once the provision of ES resulting from these scenarios was modelled, the results showed that these scenarios may potentially hamper the provision of ES in the study areas and thus exacerbate the long-term welfare of local citizens (Haines-Young and Potschin, 2010; Potschin and Haines-Young, 2013). In this case, intuitive locally-based knowledge was in contradiction with modelling outcomes, and further collaboration with stakeholders is vital to communicate potential impacts of various scenarios based on ES provision.

4.1.4 Assessment of ecosystem services and their trade-offs

This study assessed a sample of ES provided by two Czech UNESCO Biosphere Reserves and quantified their trade-offs. The ES were evaluated focusing on several representative provisioning, regulating and cultural ES (Harrison et al., 2010).

To assess provisioning and regulating ES, we adjusted and combined well-established modelling approaches introduced in scientific literature (Nemec and Raudsepp-Hearne, 2012). In the case of cultural services, the selection of modelling approaches was made more difficult by the complexity of the concept of cultural services, which includes a wide range of factors from physical character of natural landscapes to human psychological traits and processes (Bratman et al., 2012). To maintain methodological coherence with the GIS-based assessments of provisioning and regulating services in this study, we assessed cultural services utilizing spatial modelling based on physical landscape characteristics (Martín Ramos and Otero Pastor, 2012; Maes et al., 2015). In the case of landscape aesthetics, the involvement of stakeholders in preference surveys and contingent valuation exercises was beyond the scope of this study, which aimed to employ a coherent set of GIS-based methods. Thus, we did not conduct own research of landscape perceptions and fully relied on previous research elucidating people's preferences towards physical landscape characteristics, linking them to GIS-based analyses (Dramstad et al., 2006). Similarly, in the case of recreation, we solely focused on recreational potential originating from the physical features of the landscapes studied, since conducting own visitor surveys was beyond the scope of this study.

In line with previous studies, this study showed that synergies occur within the classes of regulating ES, as well as cultural ES (Rodriguez et al., 2006; Bennett et al., 2009). Unlike in other studies, an ambiguous relationship was found between provisioning services on the one hand, and cultural and regulating services on the other, emphasizing the diverse and non-linear relationships between different types of ecosystem services (Nelson et al., 2009; Goldstein et al., 2012).

The study illustrates that the most substantial aggregate increase in the provision of ES occured in scenarios assuming intensive nature protection and focus on ecosystem conservation. On the contrary, the lowest aggregate provision of ES was modelled for the scenarios assuming exploitative activities in the landscape and unsustainable economic growth. At the same time, the results suggest that similar aggregate levels of ES provision may arise from different storylines and landscape development assumptions.

4.1.5 Data and modelling limitations

The general framework of this thesis was based on the combination of diverse modelling approaches, which are inherently encumbered with limitations arising from multiple data-related issues, as well as inaccuracies arising from the design of the modelling processes (Schulp et al., 2014). The following points aim to address the main data and modelling limitations related to the analyses conducted in this study.

1. Although we aimed to utilize spatial datasets of finest available resolution, this was not possible in all cases. Therefore, datasets of multiple scales and resolution were used in the study. While some spatial datasets were available on the case-study level (e.g. tourist trails), other datasets were of coarser scale, originating from regional to national level data (e.g. climate data). The scale and resolution mismatch of input data may have introduced error in the modelling processes. In addition, differences in temporal scale of the data, as well as differences

in the time of origin of the data, influenced the accuracy and validity of the analyses.

2. The development of European-scale ALARM scenarios, used in this study as the basis for LULC modelling, started approximately a decade ago (Settele et al., 2005). Since no other array of spatially explicit scenarios of a comparably fine resolution has been developed hitherto, this set of scenarios presents the only available option to utilize in the analyses. However, it is necessary to emphasize that some of the assumptions behind these scenarios may be outdated. For instance, promotion of intensive biomass production for biofuels, outlined in the SEDG scenario, was highly promoted in the past decade in the EU, while its political support has started to be revised on the European level recently (EPRS, 2015).

3. The models utilized in this study require extensive parametrization. Although the choice of parameters was conducted based on a wide literature review, for some parameters only limited data sources were available, specific for the case study areas (e.g. average plant-root depth, carbon pools in various LULC types). In such cases, default model values or European to global scale estimates were utilized, which may have introduced another source of uncertainty in the analysis.

4. During the modelling processes, multiple operations of spatial analyses were performed (e.g. projections to different cartographic reference systems, overlay operations). During such procedures, a certain proportion of information may have been lost and the spatial accuracy of data may have decreased.

5. In the analyses in this study, only currently developed and peer-reviewed modelling approaches were applied. Nevertheless, modelling inherently presents an imperfect and simplified representation of reality. Since environmental models in general fail to represent social-ecological processes to an entirely complete and accurate level, all modelling results in this study need to be perceived as indicative (Schulp et al., 2008, 2014).

Regardless the above mentioned limitations, it should be noted that state-of-the-art modelling approaches and peer-reviewed datasets were used in this study (EEA, 2007; Spangenberg, 2007; Štěpánek et al., 2009, 2011; Bagstad, Semmens, and Winthrop, 2013; Maes et al., 2015), which ensured that the resulting analyses are comparable with other current endeavours to model and map ES and their trade-offs (Goldstein et al., 2012; Maes et al., 2015; Queiroz et al., 2015).

4.2 Follow-up research steps

The methodology proposed in this thesis represents a flexible framework, which can be further adjusted to match specific conditions of studied SES. Further development is proposed in terms of:

1. Engaging a larger and more exhaustive sample of stakeholders in participatory scenario planning,
2. Employing emerging novel methods of stakeholder involvement (Hanspach et al., 2014),
3. Utilizing forthcoming European fine-scale RCP-based LULC change scenarios, currently developed e.g. within the EU 7th Framework Programme project LUC4C (http://luc4c.eu/),
4. Applying more elaborate models for ES assessment.

Apparently, all these steps need to be taken in collaboration with researchers of diverse backgrounds within a transdisciplinary framework.

In terms of further steps, particularly the analysis of landscape aesthetics provides space for substantial future development in the conditions of the Czech Republic, towards incorporating the phenomenon of "landscape character", recognized by Czech legislation (Act no. 114/1992 Coll., on Nature and landscape protection). Landscape character refers to the complex of socio-cultural and environmental features and characteristics, defining the distinctiveness of a landscape. As such, landscape character is of high socio-cultural and environmental value, and assessments of landscape character are conducted on a regular basis in Protected Landscape Areas (AOPK ČR, 2016). Although landscape character has a strong aesthetic dimension and the assessment datasets from PLAs can be made available, they were not incorporated in the present study, since we aimed to utilize solely internationally comparable methods (which was the case of the applied methodology by (Otero Pastor et al., 2007; Martín Ramos and Otero Pastor, 2012)). Nevertheless, future research is planned to incorporate available data on landscape character in the assessment of cultural ES related to landscape aesthetics.

Třeboň Basin BR and Šumava BR present highly valuable and vulnerable areas of the Czech Republic. Since the Administrations of these protected areas are responsible for local landscape management and environmental governance, they require science-based information as an input to local decision-making. Therefore, our study aimed to support the nature conservation decision-making process and sustainable development in the selected case study areas. The preliminary results of this study have been consulted with the representatives of the Administration of Třeboň Basin PLA. At the same time, our study (as well as future assessments of ES trade-offs) aim to further contribute to the development of Třeboň Basin LTSER platform, which is currently being promoted as a successor of the local LTER site.

5 Conclusions

In the present thesis, a coherent modelling approach to analyse SES dynamics has been compiled and tested, comprising the development of alternative participatory future LULC scenarios and subsequent assessment of ES provision and trade-offs. The methodology was demonstrated on two case studies, located in Třeboň Basin UNESCO Biosphere Reserve and Šumava UNESCO Biosphere Reserve.

The study showed that the selected SES were subject to complex system dynamics, including multiple large-scale and local-scale driving forces of both anthropogenic and enviromnental character. Consequently, the applied combination of participatory and GIS-based spatial modelling approaches ensured to incorporate transdisciplinary perspectives on SES functioning.

While including stakeholders into the process of scenario storyline building ensured that locally relevant phenomena were accounted for and assessed, subsequent assessment of ES scenarios showed the potential to facilitate the prioritisation of different landscape development options in the study areas, and to provide assistance to local landscape decision-making and nature conservation planning.

In this perspective, the results showed that the most substantial aggregate increase in the provision of ES occured in scenarios assuming intensive nature protection and focus on ecosystem conservation. On the contrary, the lowest aggregate provision of ES was modelled for the scenarios assuming exploitative activities in the landscape and unsustainable economic growth. At the same time, the results suggest that similar aggregate levels of ES provision may arise from entirely different storylines and landscape development assumptions.

This thesis illustrates that the concept of ES can be applied to enrich existing research in LTSER platforms. Our pilot assessment of ES across scenarios was intended as one of the steps towards further developing LTSER platforms in Třeboň Basin UNESCO Biosphere Reserve and Šumava UNESCO Biosphere Reserve, serving as local-scale research sites of sustainable development.

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List of Appendices

Appendix I: Classifications of ecosystem services

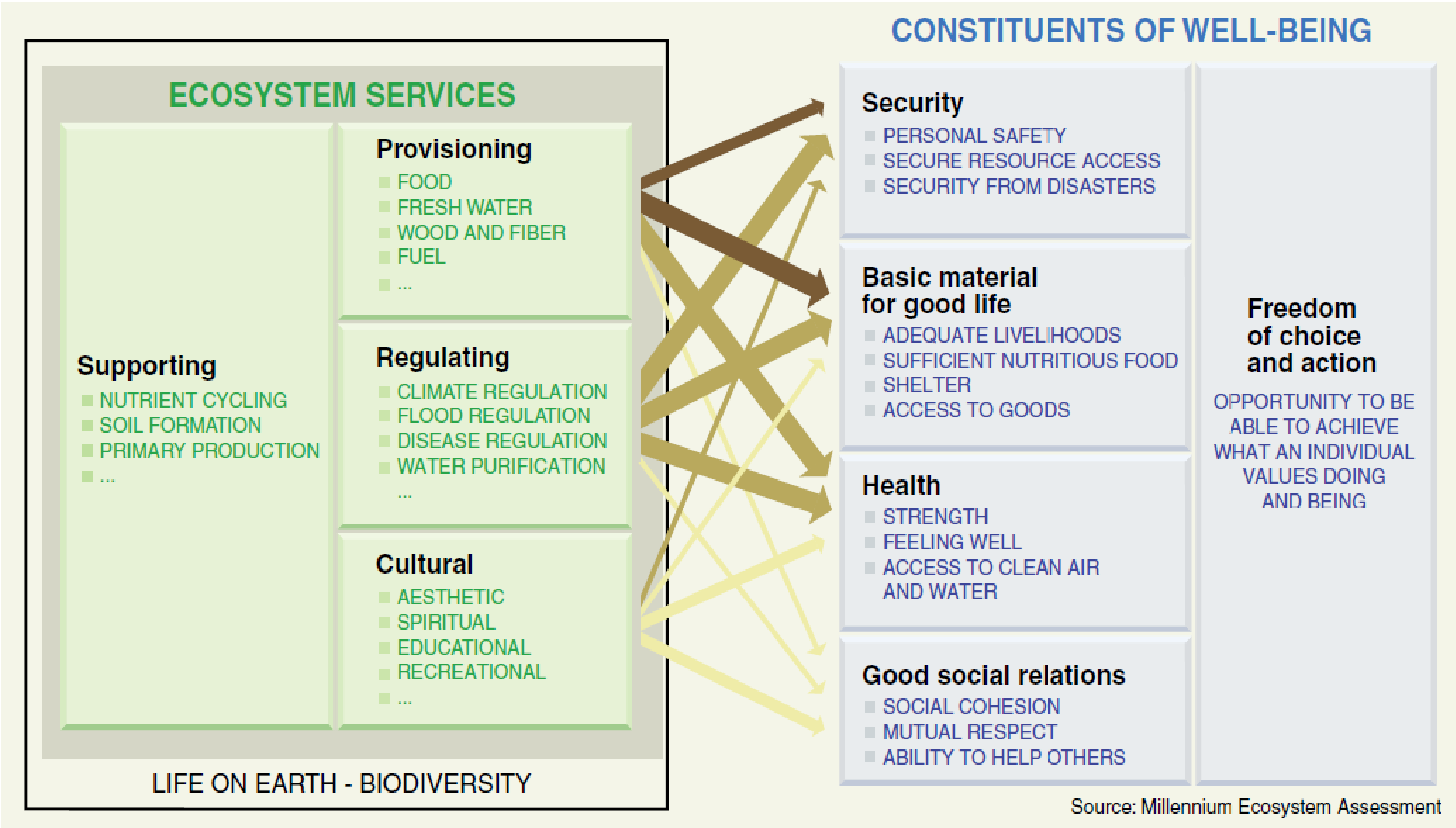

Figure A1. Summary of the Millenium Ecosystem Assessment classification of ecosystem services (according to MA, 2005)

Provisioning Services are ecosystem services that describe the material outputs from ecosystems. They include food, water and other resources.

Food: Ecosystems provide the conditions for growing food – in wild habitats and in managed agro-ecosystems.

Raw materials: Ecosystems provide a great diversity of materials for construction and fuel.

Fresh water: Ecosystems provide surface and groundwater.

Medicinal resources: Many plants are used as traditional medicines and as input for the pharmaceutical industry.

Regulating Services are the services that ecosystems provide by acting as regulators eg regulating the quality of air and soil or by providing flood and disease control.

Local climate and air quality regulation: Trees provide shade and remove pollutants from the atmosphere. Forests influence rainfall.

Carbon sequestration and storage: As trees and plants grow, they remove carbon dioxide from the atmosphere and effectively lock it away in their tissues.

Moderation of extreme events: Ecosystems and living organisms create buffers against natural hazards such as floods, storms, and landslides.

Waste-water treatment: Micro-organisms in soil and in wetlands decompose human and animal waste, as well as many pollutants.

Erosion prevention and maintenance of soil fertility: Soil erosion is a key factor in the process of land degradation and desertification.

Pollination: Some 87 out of the 115 leading global food crops depend upon animal pollination including important cash crops such as cocoa and coffee.

Biological control: Ecosystems are important for regulating pests and vector borne diseases.

Habitat or Supporting Services underpin almost all other services. Ecosystems provide living spaces for plants or animals; they also maintain a diversity of different breeds of plants and animals.

Habitats for species: Habitats provide everything that an individual plant or animal needs to survive. Migratory species need habitats along their migrating routes.

Maintenance of genetic diversity: Genetic diversity distinguishes different breeds or races, providing the basis for locally well-adapted cultivars and a gene pool for further developing commercial crops and livestock.

Cultural Services include the non-material benefits people obtain from contact with ecosystems. They include aesthetic, spiritual and psychological benefits.

Recreation and mental and physical health: The role of natural landscapes and urban green space for maintaining mental and physical health is increasingly being recognized.

Tourism: Nature tourism provides considerable economic benefits and is a vital source of income for many countries.

Aesthetic appreciation and inspiration for culture, art and design: Language, knowledge and appreciation of the natural environment have been intimately related throughout human history.

Spiritual experience and sense of place: Nature is a common element of all major religions; natural landscapes also form local identity and sense of belonging.

Figure A2. Summary of the TEEB classification of ecosystem services (according to TEEB, 2010).

Table A1. The CICES classification of ecosystem services (according to EEA, 2015).

CICES for ecosystem service mapping and assessment					
Section	**Division**	**Group**	**Class**	**Class type***	**Examples****
This column lists the three main categories of ecosystem services	***This column divides section categories into main types of output or process.***	***The group level splits division categories by biological, physical or cultural type or process.***	***The class level provides a further sub-division of group categories into biological or material outputs and bio-physical and cultural processes that can be linked back to concrete identifiable service sources.***	***Class types break the class categories into further individual entities and suggest ways of measuring the associated ecosystem service output.***	
Provisioning	Nutrition	Biomass	Cultivated crops	*Crops by amount, type*	Cereals (e.g. wheat, rye, barely), vegetables, fruits etc.
			Reared animals and their outputs	*Animals, products by amount, type*	Meat, dairy products (milk, cheese, yoghurt), honey etc.
			Wild plants, algae and their outputs	*Plants, algae by amount, type*	Wild berries, fruits, mushrooms, water cress, salicornia (saltwort or samphire); seaweed (e.g. Palmaria palmata = dulse, dillisk) for food
			Wild animals and their outputs	*Animals by amount, type*	Game, freshwater fish (trout, eel etc.), marine fish (plaice, sea bass etc.) and shellfish (i.e. crustaceans, molluscs), as well as equinoderms or honey harvested from wild populations; Includes commercial and subsistence fishing and hunting for food
			Plants and algae from in-situ aquaculture	*Plants, algae by amount, type*	In situ seaweed farming
			Animals from in-situ aquaculture	*Animals by amount, type*	In-situ farming of freshwater (e.g. trout) and marine fish (e.g. salmon, tuna) also in floating cages; shellfish aquaculture (e.g. oysters or crustaceans) in e.g. poles

		Water	Surface water for drinking	*By amount, type*	Collected precipitation, abstracted surface water from rivers, lakes and other open water bodies for drinking
			Ground water for drinking		Freshwater abstracted from (non-fossil) groundwater layers or via ground water desalination for drinking
	Materials	Biomass	Fibres and other materials from plants, algae and animals for direct use or processing	*Material by amount, type, use, media (land, soil, freshwater, marine)*	Fibres, wood, timber, flowers, skin, bones, sponges and other products, which are not further processed; material for production e.g. industrial products such as cellulose for paper, cotton for clothes, packaging material; chemicals extracted or synthesised from algae, plants and animals such as turpentine, rubber, flax, oil, wax, resin, soap (from bones), natural remedies and medicines (e.g. chondritin from sharks), dyes and colours, ambergris (from sperm whales used in perfumes); Includes consumptive ornamental uses.
			Materials from plants, algae and animals for agricultural use		Plant, algae and animal material (e.g. grass) for fodder and fertilizer in agriculture and aquaculture;
			Genetic materials from all biota		Genetic material (DNA) from wild plants, algae and animals for biochemical industrial and pharmaceutical processes e.g. medicines, fermentation, detoxification; bio-prospecting activities e.g. wild species used in breeding programmes etc.
		Water	Surface water for non-drinking purposes	*By amount, type and use*	Collected precipitation, abstracted surface water from rivers, lakes and other open water bodies for domestic use (washing, cleaning and other non-drinking use), irrigation, livestock consumption, industrial use (consumption and cooling) etc.
			Ground water for non-drinking purposes		Freshwater abstracted from (non-fossil) groundwater layers or via ground water desalination for domestic use (washing, cleaning and other non-drinking use), irrigation, livestock consumption, industrial use (consumption and cooling) etc.
	Energy	Biomass-based energy sources	Plant-based resources	*By amount, type, source*	Wood fuel, straw, energy plants, crops and algae for burning and energy production
			Animal-based resources		Dung, fat, oils, cadavers from land, water and marine animals for burning and energy production
		Mechanical energy	Animal-based energy	*By amount, type, source*	Physical labour provided by animals (horses, elephants etc.)

Regulation & Maintenance	Mediation of waste, toxics and other nuisances	Mediation by biota	Bio-remediation by micro-organisms, algae, plants, and animals	*By amount, type, use, media (land, soil, freshwater, marine)*	Bio-chemical detoxification/decomposition/mineralisation in land/soil, freshwater and marine systems including sediments; decomposition/detoxification of waste and toxic materials e.g. waste water cleaning, degrading oil spills by marine bacteria, (phyto)degradation, (rhizo)degradation etc.
			Filtration/sequestration /storage/accumulation by micro-organisms, algae, plants, and animals	*By amount, type, use, media (land, soil, freshwater, marine)*	Biological filtration/sequestration/storage/accumulation of pollutants in land/soil, freshwater and marine biota, adsorption and binding of heavy metals and organic compounds in biota
		Mediation by ecosystems	Filtration/sequestration /storage/accumulation by ecosystems	*By amount, type, use, media (land, soil, freshwater, marine)*	Bio-physicochemical filtration/sequestration/storage/accumulation of pollutants in land/soil, freshwater and marine ecosystems, including sediments; adsorption and binding of heavy metals and organic compounds in ecosystems (combination of biotic and abiotic factors)
			Dilution by atmosphere, freshwater and marine ecosystems		Bio-physico-chemical dilution of gases, fluids and solid waste, wastewater in atmosphere, lakes, rivers, sea and sediments
			Mediation of smell/noise/visual impacts		Visual screening of transport corridors e.g. by trees; Green infrastructure to reduce noise and smells
	Mediation of flows	Mass flows	Mass stabilisation and control of erosion rates	*By reduction in risk, area protected*	Erosion / landslide / gravity flow protection; vegetation cover protecting/stabilising terrestrial, coastal and marine ecosystems, coastal wetlands, dunes; vegetation on slopes also preventing avalanches (snow, rock), erosion protection of coasts and sediments by mangroves, sea grass, macroalgae, etc.
			Buffering and attenuation of mass flows		Transport and storage of sediment by rivers, lakes, sea
		Liquid flows	Hydrological cycle and water flow maintenance	*By depth/ volumes*	Capacity of maintaining baseline flows for water supply and discharge; e.g. fostering groundwater; recharge by appropriate land coverage that captures effective rainfall; includes drought and water scarcity aspects.

			Flood protection	*By reduction in risk, area protected*	Flood protection by appropriate land coverage; coastal flood prevention by mangroves, sea grass, macroalgae, etc. (supplementary to coastal protection by wetlands, dunes)
		Gaseous / air flows	Storm protection	*By reduction in risk, area protected*	Natural or planted vegetation that serves as shelter belts
			Ventilation and transpiration	*By change in temperature/humidity*	Natural or planted vegetation that enables air ventilation
	Maintenance of physical, chemical, biological conditions	Lifecycle maintenance, habitat and gene pool protection	Pollination and seed dispersal	*By amount and source*	Pollination by bees and other insects; seed dispersal by insects, birds and other animals
			Maintaining nursery populations and habitats	*By amount and source*	Habitats for plant and animal nursery and reproduction e.g. seagrasses, microstructures of rivers etc.
		Pest and disease control	Pest control	*By reduction in incidence, risk, area protected*	Pest and disease control including invasive alien species
			Disease control		In cultivated and natural ecosystems and human populations
		Soil formation and composition	Weathering processes	*By amount/concentration and source*	Maintenance of bio-geochemical conditions of soils including fertility, nutrient storage, or soil structure; includes biological, chemical, physical weathering and pedogenesis
			Decomposition and fixing processes		Maintenance of bio-geochemical conditions of soils by decomposition/mineralisation of dead organic material, nitrification, denitrification etc.), N-fixing and other bio-geochemical processes;
		Water conditions	Chemical condition of freshwaters	*By amount/ concentration and source*	Maintenance / buffering of chemical composition of freshwater column and sediment to ensure favourable living conditions for biota e.g. by denitrification, re-mobilisation/re-mineralisation of phosphorous, etc.
			Chemical condition of salt waters		Maintenance / buffering of chemical composition of seawater column and sediment to ensure favourable living conditions for biota e.g. by denitrification, re-mobilisation/re-mineralisation of phosphorous, etc.
		Atmospheric composition and climate regulation	Global climate regulation by reduction of greenhouse gas concentrations	*By amount, concentration or climatic parameter*	Global climate regulation by greenhouse gas/carbon sequestration by terrestrial ecosystems, water columns and sediments and their biota; transport of carbon into oceans (DOCs) etc.
			Micro and regional climate regulation		Modifying temperature, humidity, wind fields; maintenance of rural and urban climate and air quality and regional precipitation/temperature patterns

Cultural	Physical and intellectual interactions with biota, ecosystems, and land-/seascapes [environmental settings]	Physical and experiential interactions	Experiential use of plants, animals and land-/seascapes in different environmental settings	*By visits/use data, plants, animals, ecosystem type*	In-situ whale and bird watching, snorkelling, diving etc.
			Physical use of land-/seascapes in different environmental settings		Walking, hiking, climbing, boating, leisure fishing (angling) and leisure hunting
		Intellectual and representative interactions	Scientific	*By use/citation, plants, animals, ecosystem type*	Subject matter for research both on location and via other media
			Educational		Subject matter of education both on location and via other media
			Heritage, cultural		Historic records, cultural heritage e.g. preserved in water bodies and soils
			Entertainment		Ex-situ viewing/experience of natural world through different media
			Aesthetic		Sense of place, artistic representations of nature
	Spiritual, symbolic and other interactions with biota, ecosystems, and land-/seascapes [environmental settings]	Spiritual and/or emblematic	Symbolic	*By use, plants, animals, ecosystem type*	Emblematic plants and animals e.g. national symbols such as American eagle, British rose, Welsh daffodil
			Sacred and/or religious		Spiritual, ritual identity e.g. 'dream paths' of native Australians, holy places; sacred plants and animals and their parts
		Other cultural outputs	Existence	*By plants, animals, feature/ecosystem type or component*	Enjoyment provided by wild species, wilderness, ecosystems, land-/seascapes
			Bequest		Willingness to preserve plants, animals, ecoystems, land-/seascapes for the experience and use of future generations; moral/ethical perspective or belief

*Note: this section is open in that many class types can potentially be recognised and nested in the higher level classes, depending on the ecosystems being considered.

**Note: this section is not complete and for illustrative purposes only. Key components could change by region or ecosystem.

Table A2. The CICES classification of ecosystem services and its parallels to the MA and TEEB classifications (according to EEA, 2015).

Section	Division	Group	Class	MA	TEEB
Provisioning	Nutrition	Biomass	Cultivated crops	Food	Food
			Reared animals and their outputs		
			Wild plants, algae and their outputs		
			Wild animals and their outputs		
			Plants and algae from in-situ aquaculture		
			Animals from in-situ aquaculture		
		Water	Surface water for drinking	Water	Water
			Ground water for drinking		
	Materials	Biomass	Fibres and other materials from plants, algae and animals for direct use or processing	Fibre, Timber, Ornamental, Biochemical	Raw materials, medicinal resources
			Materials from plants, algae and animals for agricultural use		
			Genetic materials from all biota	Genetic materials	Genetic materials
		Water	Surface water for non-drinking purposes	Water	Water
			Ground water for non-drinking purposes		
	Energy	Biomass-based energy sources	Plant-based resources	Fibre	Fuels and fibres
			Animal-based resources		
		Mechanical energy	Animal-based energy		
Regulation & Maintenance	Mediation of waste, toxics and other nuisances	Mediation by biota	Bio-remediation by micro-organisms, algae, plants, and animals	Water purification and water treatment, air quality regulation	Water purification and water treatment, air quality regulation
			Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals		
		Mediation by ecosystems	Filtration/sequestration/storage/accumulation by ecosystems		
			Dilution by atmosphere, freshwater and marine ecosystems		
			Mediation of smell/noise/visual impacts		
	Mediation of flows	Mass flows	Mass stabilisation and control of erosion rates	Erosion regulation	Erosion prevention
			Buffering and attenuation of mass flows		
		Liquid flows	Hydrological cycle and water flow maintenance	Water regulation	Regulation of water flows, regulationof extreme events
			Flood protection	Natural hazard regulation	
		Gaseous / air flows	Storm protection		
			Ventilation and transpiration		

	Maintenance of physical, chemical, biological conditions	Lifecycle maintenance, habitat and gene pool protection	Pollination and seed dispersal	Pollination	Pollination
			Maintaining nursery populations and habitats		
		Pest and disease control	Pest control	Pest regulation	Biological control
			Disease control	Disease regulation	
		Soil formation and composition	Weathering processes	Soil formation [supporting services]	Maintenance of soil fertility
			Decomposition and fixing processes		
		Water conditions	Chemical condition of freshwaters	Water regulation	Water
			Chemical condition of salt waters		
		Atmospheric composition and climate regulation	Global climate regulation by reduction of greenhouse gas concentrations	Atmospheric regulation	Climate regulation
			Micro and regional climate regulation	Air quality regulation	Air quality regulation
Cultural	Physical and intellectual interactions with biota, ecosystems, and land-/seascapes [environmental settings]	Physical and experiential interactions	Experiential use of plants, animals and land-/seascapes in different environmental settings	Recreation and ecotourism	Recreation and tourism
			Physical use of land-/seascapes in different environmental settings		
		Intellectual and representative interactions	Scientific	Knowledge systems and educational values, cultural diversity, aesthetic values	Inspiration for culture, are and design, aesthetic information
			Educational		
			Heritage, cultural		
			Entertainment		
			Aesthetic		
	Spiritual, symbolic and other interactions with biota, ecosystems, and land-/seascapes [environmental settings]	Spiritual and/or emblematic	Symbolic	Spiritual and religious values	Information and congnitive development
			Sacred and/or religious		
		Other cultural outputs	Existence		
			Bequest		

Appendix II: List of peer-reviewed publications related to the thesis

HARMÁČKOVÁ, Z.V., KRKOŠKA LORENCOVÁ, E., VAČKÁŘ, D. (in press). Ecosystem-based adaptation and disaster risk reduction: Costs and benefits of participatory ecosystem services scenarios for Šumava National Park, Czech Republic. In: RENAUD, F., SUDMEIER-RIEUX, K., ESTRELLA, M., NEHREN, U. (Eds.). *Ecosystem-based disaster risk reduction and adaptation: linking science, policy and practice*. Springer.

HARMÁČKOVÁ, Z.V., VAČKÁŘ, D. Assessing regulating ecosystem service trade-offs across landscape scenarios in Třeboňsko Biosphere Reserve, Czech Republic. *Ecological Modelling*. 2015, vol. 295, pp. 207–215.

VAČKÁŘ, D., HARMÁČKOVÁ, Z.V., KAŇKOVÁ, H., STUPKOVÁ, K. Human transformation of ecosystems: comparing protected and unprotected areas with natural baselines. *Ecological Indicators*. 2016, vol. 66, pp. 321–328.

KRKOŠKA LORENCOVÁ, E., HARMÁČKOVÁ, Z.V., LANDOVÁ, L., PÁRTL, A., VAČKÁŘ, D. Assessing impact of land use and climate change on regulating ecosystem services in the Czech Republic. *Ecosystem Health and Sustainability*. 2016, vol. 2, p. e01210.

FRÉLICHOVÁ, J., VAČKÁŘ, D., PÁRTL, A., LOUČKOVÁ, B., HARMÁČKOVÁ, Z.V., LORENCOVÁ, E. Integrated assessment of ecosystem services in the Czech Republic. *Ecosystem Services*. 2014, vol. 8, pp. 110–117.